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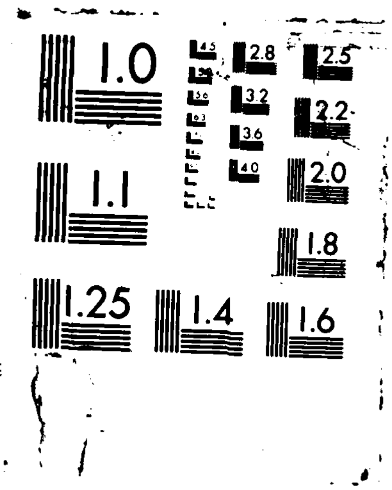
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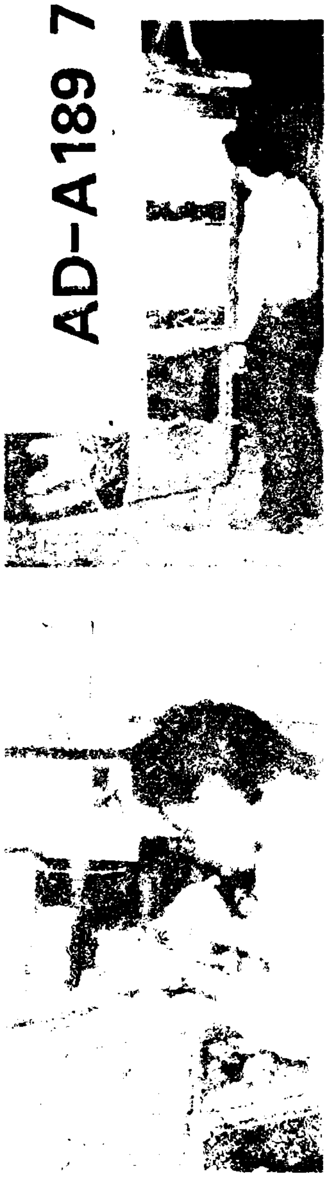

STRUCTURES LABORATORY

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PROPERTIES OF LABORATORY-TESTED SPECIMENS OF CONCRETE FROM SMALL-SCALE SEAL PERFORMANCE TESTS AT THE WASTE ISOLATION PILOT PLANT

by

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Development and field placement of a salt-saturated concrete at the Waste Isolation Pilot Plant (WIPP) included extensive testing of field-cast specimens in the laboratory. Such test specimens were cast during two field events, each part of the Small-Scale Seal Performance Tests (SSSPT) at the WIPP, designated Test Series A and B. This report presents data from laboratory tests of SSSPT specimens at ages of three days to one year. The concrete maintained desired physical properties throughout the testing program, maintaining a volume increase and achieving a compressive strength of near 7,000 psi at one year. Data were analyzed by a curve-fitting computer program, and are presented in figures showing best-fitting curves, which are models of the concrete properties with time. Keywords:

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PREFACE

The work described in this report is part of an ongoing research effort accomplished in the Concrete Technology Division (CTD), Structures Laboratory (SL), US Army Engineer Waterways Experiment Station (WES), under contract to Sandia National Laboratories (SNL), Albuquerque, New Mexico. Mr. John Stormont was SNL Technical Monitor for field and laboratory activities, which occurred between July 1985 and February 1987.

Mr. Donald M. Walley and Dr. Lillian D. Wakeley, SL, CTD, directed laboratory development of the concrete and field activities during which specimens described in this report were cast. Other CTD personnel participating in these activities included Messrs. Brian Green, Percy Collins, Donnie Ainsworth, Larry Crittenden, Mike Lloyd, Cliff Gill, and Bill Neeley. Dr. Carl Pace was responsible for laboratory testing, which was accomplished by Linda Mayfield, Benny Neal, John Cook, and Gregory Comes.

The work was under the general supervision of Kenneth Saucier, Chief, Concrete and Evaluation Group of the CTD; John M. Scanlon, Chief, CTD; James T. Ballard, Assistant Chief, SL; and Bryant Mather, Chief, SL. Mr. Comes and Edward F. O'Neil, III, accomplished the reduction of data. They and Dr. Wakeley prepared this report.

COL Dwayne G. Lee is Commander and Director of WES. Dr. Robert Whalin is Technical Director.

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CONVERSION FACTORS, NON-SI TO SI (METRIC)

UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
feet	0.3048	metres
inches	25.4	millimetres
pounds (force) per square inch	0.006894757	megapascals
pounds (mass) per cubic foot	16.018463	kilograms per cubic metre

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

PROPERTIES OF LABORATORY-TESTED SPECIMENS OF CONCRETE FROM SMALL-SCALE SEAL PERFORMANCE TESTS AT THE WASTE ISOLATION PILOT PLANT

INTRODUCTION

Background

1. The U.S. Department of Energy (DOE) is developing the Waste Isolation Pilot Plant (WIPP) as a research and development facility to demonstrate the safe disposal of radioactive wastes resulting from defense activities. The WIPP repository facility is located in bedded rock salt (halite), approximately 2,150 ft* (656 m) below the ground surface, near Carlsbad, New Mexico.

2. Since 1975, the U.S. Army Engineer Waterways Experiment Station (WES) has been involved in research on and development of cement-based grouts and concretes for use at the WIPP, in cooperation with Sandia National Laboratories (SNL). WES is currently participating in the SNL Plugging and Sealing Program in support of the WIPP project. The objectives of the Plugging and Sealing Program are (Stormont 1986):

- a. To develop candidate sealing materials.
- b. To evaluate relevant host-rock properties.
- c. To assess long-term geochemical and mechanical stability of candidate materials.
- d. To evaluate emplacement techniques and performance of candidate materials.
- e. To provide design information of an expansive concrete plug and salt rock for seals.
- f. To assess the impact of leakage resulting from existing penetrations on the performance of the repository system.

3. The Small-Scale Seal Performance Tests (SSSPT), which are a part of this program, are a series of in situ experiments designed to evaluate the performance of various candidate seal materials (Stormont 1985). The objectives of the Small-Scale Seal Performance Tests are:

- a. To determine the in situ fluid flow performance for various sealing systems, including evaluating flow paths, difference between gas and brine permeabilities, and scaling effects;

---

* A table of factors for converting non-SI units of measurements to SI (metric) units is presented on page 6 .

b. To determine the in situ mechanical performance of the host-rock and seal materials, including evaluating bond strength and size effects;

c. To assess seal emplacement techniques;

d. To support the development of numerical predictive capabilities.

4. The first two of five seal emplacements underground at the WIPP repository horizon for the SSSPT were Test Series A and B. These emplacements were completed July 31, 1985 and February 28, 1986, respectively. The seal material used for these tests was an expansive salt-saturated concrete (ESC) developed at the WES for use at the WIPP repository horizon. The development and field placement of ESC is described by Wakeley and Walley (1986) and Stormont (1986).

Test Series A

5. Test Series A was designed to evaluate the performance of ESC seals in vertical boreholes. Six concrete plugs were emplaced in the host rock: two each, of 6 in. (152 mm), 16 in. (406 mm) and 36 in. (914 mm) diameter, with lengths of 1 ft (305 mm), 2 ft (610 mm), and 3 ft (914 mm), respectively. Instrumentation was embedded in one seal of each size. The instruments measured the thermal and mechanical characteristics of the ESC seals and interaction with the host rock. The methods of instrumentation and calculations are described by Ainsworth (1987). Field placement of the instruments and plans for permeability testing are described by Stormont (1986).

Test Series B

6. Test Series B provided an opportunity to evaluate the same parameters as Test Series A, but with the seals in a horizontal orientation. ESC was pumped into two boreholes, each 36 in. (914 mm) in diameter, one of which was instrumented as in Series A. In practice, both horizontal and vertical seals may be used for waste disposal. These configurations require different placement techniques. The materials are affected differently by the placement techniques and by gravity (Wakeley and Walley 1986). An experimental method for determining expansive properties of a seal material in a restrained environment is described by Pace and Gulick (1985).

Objectives

7. This is a data report. Limited analysis of data was accomplished by fitting mathematical curves to the data. This report presents data from laboratory tests of specimens of ESC cast in the field to accompany Test Series A and B. The information contained herein is intended to be used by others in analyses of the seal system performance. Data from measurements of engineering properties of the field-cast specimens of ESC include those of compressive strength (f'_c), static modulus of elasticity (E_s), dynamic modulus of elasticity (E_d), Poisson's ratio (μ), and length change. These data are reported in tables, and in figures depicting fit to specified curves, as explained in the Discussion section of this report.

CONCRETE COMPONENTS AND MIXTURE PROPORTIONS

8. Components of ESC have been identified as having characteristics considered beneficial to cement-based materials for use in the Plugging and Sealing Program. The mixture components and proportions of ESC from which the test specimens were cast are presented in Table 1. Wakeley and Walley (1986) described the components of ESC and the reasons for their use, as follows:

- a. Class H oil-well cement, chosen for low fineness, low water demand, sulfate resistance, availability, and long history of successful commercial use.
- b. Class C fly ash (ASTM C 618) with high calcium oxide content, was selected for its anticipated contribution to chemical expansion, availability at a reasonable distance from the WIPP site, and uniform composition over time. It was supplied by Southwest Public Service.
- c. Cal Seal (a trade name for calcium sulfate hemihydrate) and ChemComp III both were intended to contribute to the expansion of the concrete, and give favorable results when used with Class H cement and high-lime fly ash.
- d. Granular sodium chloride is added so that the mixture is saturated with this salt, and can be placed in contact with halite rock without dissolving the rock at the interface. Secondarily, it contributes to the workability and expansiveness of the mixture.
- e. De-Air #1 is a proprietary air-detraining agent of Halliburton Services, Inc. In conjunction with other admixtures used in ESC, this component allows mixing for up to 3 hours while keeping air content below 3 percent.

f. The sand and gravel used as aggregates in ESC are commercially available near the WIPP site, and have no noticeable deleterious effects on the concrete.

g. Sodium citrate acts as both a set retarder and a water-reducing agent in ESC. It is used in lieu of other, more recently developed and marketed organic chemical admixtures for these purposes.

RESULTS OF LABORATORY TESTS OF FIELD-CAST SPECIMENS

9. A total of 102 ESC test specimens were cast in the field during the Test Series A seal emplacement, and 141 from Test Series B emplacement. The tests listed in "objectives" were performed at ages of 3 to 374 days after casting. Table 2 presents the type, size and number of specimens cast for each test series. The tables and figures giving test results are grouped in Appendices A through J, according to the Test Series, size, and type of mold.

Casting and Handling Test Specimens

Test Series A

10. Specimens from Test Series A were cured underground at the repository temperature and humidity of approximately 82°F (27.8°C) and <50 percent r.h. for two days before being transported to the WES in Vicksburg, Mississippi. Although great effort had been expended to minimize the handling and placing problems of the fresh concrete in the field (Stormont 1985), the relatively slow delivery and long haul distances in warm conditions between initial mixing and eventual placing caused a loss of slump, and therefore decreased the workability. Laboratory test specimens for Test Series A were cast approximately 4 hr after the initial introduction of the mixing water, after all concrete plugs had been emplaced in the rock. The slump had decreased from an initial 10-1/2 in. (267 mm) to 4 in. (102 mm) when the last specimens were cast.

11. Specimens were then demolded, and most were cured at 74°F (23°C). Departures from the originally intended test plan led to inconsistencies in curing and storage procedures, which adversely affected the continuity of data accumulation at early ages. This did not appear to cause any problem over the longer term (see Discussion).

Test Series B

12. Specimens from Test Series B were cast underground at the WIPP, with all exposed surfaces coated with a curing compound to minimize gain or loss of moisture. After 24 hours underground, they were transported to WES. The temperature was monitored during transporation, and not allowed to rise above 81°F (27.8°C). Upon arrival at WES, the specimens were maintained in their molds in an 81°F environment, to simulate field conditions. This control was maintained for all specimens until they were demolded, immediately before the time of testing.

13. Test Series B specimens were cast approximately 3 hr after the initial introduction of the mixing water. The initial slump of the ESC prepared for Test Series B was 10.5 in. (267 mm), and the slump at the time of casting was 8.5 in. (216 mm).

Compressive Strength of Cylindrical Concrete Specimens

14. All compressive strength tests were conducted in accordance with test method ASTM C 39-84 (CRD-C 14-84) "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens." A total of 42 specimens from Test Series A and 62 from Test Series B had been tested for compressive strength at the time this report was prepared. The average compressive strength of two 4- by 8-in. (102- by 203-mm) cylindrical specimens from Test Series A cast in plastic molds was 3,520 psi (24.3 MPa) at 29 days of age, and 6,800 psi (46.9 MPa) at 366 days of age. A single 4- by 8-in. test cylinder cast in a plastic mold from Test Series A had a compressive strength of 7,320 psi (505 MPa) at 251 days of age. The average compressive strength of two 4- by 8-in. specimens from Test Series B, cast in plastic molds, was 3,860 psi (26.6 MPa) at 28 days. The average compressive strength of three 6- by 12-in. (152- by 305-mm) specimens from Series B, cast in steel molds, was 7,400 psi (51.0 MPa) at 374 days of age.

15. Figures showing the increase in compressive strength with time for field-cast cylindrical specimens from Test Series A and B are presented in Appendix A. A complete tabular presentation of these data for compressive strength is in Appendix B.

16. A difference in compressive strength was noted between cylinders cast in plastic molds for Test Series B and others cast in steel molds. Based

on past studies, differences in compressive strength of conventional concrete specimens cast in steel and plastic molds have been found to be on the order of 13 percent (Mather 1975). ESC specimens cast in 6- by 12-in. (152- by 305-mm) steel molds and tested at 28 days of age were found to have compressive strengths as much as 25 percent greater than those of specimens of the same age cast in 6- by 12-in. plastic molds.

Static Modulus of Elasticity and Poisson's Ratio

17. The static modulus of elasticity and Poisson's ratio were determined for all specimens in accordance with test method ASTM 469-81 (CRD-C 19-83), "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression." The stress and strain relationships used to determine static modulus of elasticity and Poisson's ratio were recorded during the testing of ESC specimens for compressive strength.

18. A total of 39 specimens from Test Series A and 60 specimens from Test Series B were tested for static modulus of elasticity. Static modulus of elasticity plotted vs specimen age are presented in Appendix C. The test results are presented in tabular form in Appendix D. Figures showing Poisson's ratio are in Appendix E, with corresponding Tables in Appendix F.

Dynamic Modulus of Elasticity

19. The method used to determine the dynamic modulus of elasticity is described by Ainsworth (1986). Graphical representations of E_d vs time for Test Series A and Test Series B are presented in Appendix G, with Tables in Appendix H.

Linear Expansion

20. Tests of restrained expansion were performed in accordance with ASTM C 806-75 (CRD-C 225-76) for specimens cast with Test Series B. Storage conditions were modified as described previously, and specimens had a 3-in.-square cross section (76 by 76 mm). These specimens were monitored for length change to 90 days age. Data are in Appendix I.

21. Additional specimens were cast during field activities of Test Series B to investigate the relationship between expansion and restraint.

Restraint was varied by use of restraining rods with four different diameters: 3/16 in. (4.8 mm), for the standard test specimens described previously; and 1/4- (6.4-mm), 3/8- (9.5-mm), and 1/2-in. (12.7-mm) rods, enclosed in 3- by 3- by 10-in. concrete prisms. Unrestrained prisms also were cast and all were monitored to 90 days age.

22. Expansion prisms with the 1/2-in. restraining rod allowed approximately 0.02 percent expansion, where the unrestrained expansion bar expanded 0.38 percent. Nearly all of the expansion occurred during the first 10 days after casting with only slight changes in length over long periods of time. Figure I1, in Appendix I summarizes the relationships between expansion and restraint over time, and shows an inverse relationship between restraint and expansion.

DISCUSSION

Differences Between the Two Series of Data

23. Differences in measured properties of specimens from Test Series A and B were expected, due to differences in casting and curing. The elapsed time between the addition of mixing water and casting of specimens was longer for Test Series A, and slump had decreased, as was mentioned previously. This has been shown to decrease linear expansion (Wakeley 1987), although its impact on other properties has not been explored. However, measured values of most properties are similar for the two Test Series at comparable times.

24. For Test Series A, ESC was placed using a series of buckets, hoppers, and tremies, and the concrete cast into laboratory specimens was treated in the same manner. The horizontal boreholes of Test Series B required that the concrete was placed using a concrete pump. All laboratory specimens from Test Series B were cast from the ESC sampled at the point of discharge from the line from the pump. Because of the potential for these variables to affect the test results, data from the two Series may not be directly comparable. They are similar for most properties, however, especially from longer-term tests.

25. At one year, compressive strength of cylinders from Series A and B differ very little (6,860 vs 7,400 psi), with the difference as readily explained by plastic vs steel molds as by differences in casting or curing.

For each test for which longer-term data are available, the variability observed within data from one Series does not appear to detract from the curve-fitting process. Comparing data from Series A and B, the observed early-age differences, appear to diminish with time.

Regression Analysis and Generation of Curves

Using the CURVFIT program

26. Data used in the regression analyses are presented in Appendices A through H. These appendices present the data in tabular form, and also plotted as a function of time. For those data that could be correlated with a mathematical function, the plots are augmented with a best-fit curve through the data points. The best-fit curves were chosen from a series of curves calculated to fit the data by a computer program, called "CURVFIT," which was developed by the Information Technology Laboratory of the WES (Renner, 1979).

27. This computer program is a general purpose statistical-analysis and curve-fitting code for problems involving two variables. It analyzes the input data and provides correlation statistics for the appropriate fit to nine curve models (polynomial of degree 1 (linear fit), two polynomial curves, exponential, power, two common logarithmic equations, one natural logarithmic equation, and a hyperbolic function). This allows the user to evaluate which curve best fits the data. To aid the user in evaluation of these curves, the program provides the non-linear correlation, the standard error estimate, and the sum of the squares of the residuals, as indicators of fit of the data to the calculated curve.

28. Standard deviation lines, representing the boundaries of one, two, or three standard deviations from the fitted curve, can be plotted on the curve. For this report, the lines representing one standard deviation were plotted, and appear as dashed lines. Appendix J gives the equations chosen to best represent the data for each category of data where a correlation could be found. These curves are numerical models relating the behavior of the material properties to time. They can predict, with a reasonable amount of certainty, how the properties will behave with time. The information in this appendix also includes the non-linear correlation and the standard error estimate.

29. Table 3 presents the curve models used by the computer program. Detailed explanation of the methods used by CURVFIT is given by Renner (1979).

Choosing the best-fit curve

30. The non-linear correlation coefficient, and the characteristics of the curves from the CURVFIT program, were the properties used to select the curve which best fit the test data. The correlation coefficient manifests itself as a value ranging from 0.00 to 1.00, depending upon the closeness of the test data to hypothetical points which lie on the selected curve. A value of 1.00 represents perfect fit of test and hypothetical (model) data, while low values indicate no correlation of the data to any of the curves. Values in-between represent degrees of fit which range from poor to very good.

31. It is a matter of interpretation how one determines what is a good fit. For the correlations conducted in this study, a coefficient above 0.95 was considered a very good fit, correlations above 0.90 were considered a good fit, and correlations which were lower than 0.85 were considered too low to be used as a model for estimating material-property behavior.

32. The correlation coefficient was not the only factor used to select the best model. The characteristic behavior of the curve in relation to the expected behavior of the particular material property being modeled also was an evaluative criterion. An example is shown in Figure 1. This figure is a composite of the five curves with the highest correlation coefficients for compressive strength versus time of Series A, 6- by 12-in. specimens. The highest correlation coefficient was earned by curve number 1 which was a polynomial of degree 2. However, this curve indicates decreasing compressive strength with age beyond approximately 320 days. This characteristic is not typical of concrete, which continues to gain strength with age. Consequently, this curve was rejected.

33. Similarly, the exponential curve (curve number 5) shows the concrete gaining strength very slowly at early age, and then beginning to exhibit more rapid strength gain as time progresses. This also is non-characteristic of how concrete gains strength, which is normally rapid at early age and less active (but still increasing) at advanced age (one year and beyond).

34. In this example, the power curve (curve number 4) was considered the most representative of the normal behavior of compressive strength gain with

time, and was the model chosen as the best fit of the data. Even though this curve was not the highest in data correlation, all three curves which reasonably matched the characteristics behavior of the concrete were above 0.98 in goodness of fit, and within a range of 0.005 of each other.

Reporting Poisson's ratio

35. The plots of Poisson's ratio of all concrete specimens tested are presented in Appendix E. These plots show only original data points in a scatter diagram, without any correlation curve. The non-linear correlation coefficients for all these groups of tests ranged between 0.10 and 0.66, falling outside the definition of fitting the characteristics of any of the nine models. This merely indicates that there is no correlation of Poisson's ratio of concrete with time.

36. Neville (1981) states that there are very few reliable data available on the variation of Poisson's ratio with time, and that in general the ratio is unaffected by time. The data gathered here tend to reinforce that observation, and as such were not given model curves. Neville also states that normally the value of the ratio falls between 0.11 and 0.21. The extremes of the data gathered here are 0.12 and 0.33. The higher ratios presented here are at advanced ages, and may result from the expansive nature of this concrete.

Other problems

37. Figure C1, of static modulus, also shows no curve recommended, for the reasons given above.

38. The nine curves of CURVFIT, fitted to the data given in Table D5, all had correlation coefficients in 0.79 to 0.90 range. However, all curves plotted to these data were uncharacteristic of the behavior of static modulus of concrete with time. Further observation of data in Table D5 led to the suspicion that static modulus of 2.5×10^6 psi at 14 days age was not consistent with the other two values at this age, and that a new analysis should be conducted, excluding this point. The correlations improved to acceptable levels of 0.87 to 0.97, and the curves representing the time history trends became more characteristic. As a result of this modification of the data, a common logarithmic curve was fitted to the remaining data, with a correlation of 0.92. This is the only modification of the data for the entire set of figures.

Using These Curves as Models

39. Curves generated from regression analysis are based on one range of data and in this case yield models of the behavior of the test material during this specified range of time. It cannot be stated that the curves generated in this study will accurately predict behavior outside of that range. However, it is possible to increase the probability of good fit over an extended range of data if hypothetical data points are generated, based on the best engineering judgement of how the material should behave in the extended range. Simulation modeling of this nature could be based on both physical and hypothetical data, and extrapolated to provide regression curves for longer periods of time not achievable through physical testing.

SUMMARY

40. Specimens of concrete cast in the field at the WIPP site were tested in the laboratory at ages of three days to one year. These specimens represented the concrete placed for field tests of vertical and horizontal borehole plugs in bedded salt. Data from laboratory tests include compressive strength, static and dynamic moduli, Poisson's ratio, and restrained linear expansion.

41. The concrete was formulated with expansive admixtures and sodium chloride. It gained strength and continued to expand throughout the test period. The data are included in the appendices, in tables and as curves generated by regression analysis. Differences between data from the two test series are less than might have been expected, given the differences in handling and casting the test specimens. The analyses of the data could be used for predictive modeling of concrete behavior with time.

REFERENCES

Ainsworth, Donnie L. 1986. "Field Measurement of Creep and Dynamic E on Field Cast Specimens from Concrete used for 36-in. Seal Emplacement Holes for Test Series B," WIPP Procedure No. 41, Sandia National Laboratories, Albuquerque, New Mexico.

__________. 1987. "Development and Implementation of Instrumentation for WIPP Test Series A of the Small Scale Seal Performance Tests," Technical Report SL-87-__ (in preparation), U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Mather, Bryant. 1976 (Jan). Letter to Mr. B. S. Helms, Bechtel Power Corp.

Neville, Adam. 1981. Properties of Concrete, 3rd Edition, Pitman Publishing, London, England.

Pace, Carl E., and Gulick, Charles W., Jr. 1985. "Expansive Grout Plug Effects in Restrained Environments," Technical Report SL-85-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Renner, Robert. 1979 (Nov). "Users' Guide for the Interactive Computer Program CURVFIT," Instruction Report O-79-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Stormont, John C. 1985. "Test Plan: Small Scale Seal Performance Tests (SSSPT)," Sandia National Laboratories, Albuquerque, New Mexico.

__________. 1986 (May). "Development and Implementation: Test Series A of the Small Scale Seal Performance Tests," SAND85-2602, Sandia National Laboratories, Albuquerque, New Mexico.

Wakeley, Lillian D., and Walley, Donald M. 1986 (Sep). "Development and Field Placement of an Expansive Salt-Saturated Concrete (ESC) for the Waste Isolation Pilot Plant (WIPP)," Technical Report SL-86-36, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Wakeley, Lillian D. 1987 (July). "Dependence of Expansion of a Salt-Saturated Concrete on Temperature and Mixing and Handling Procedures," Technical Report SL-87-20, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

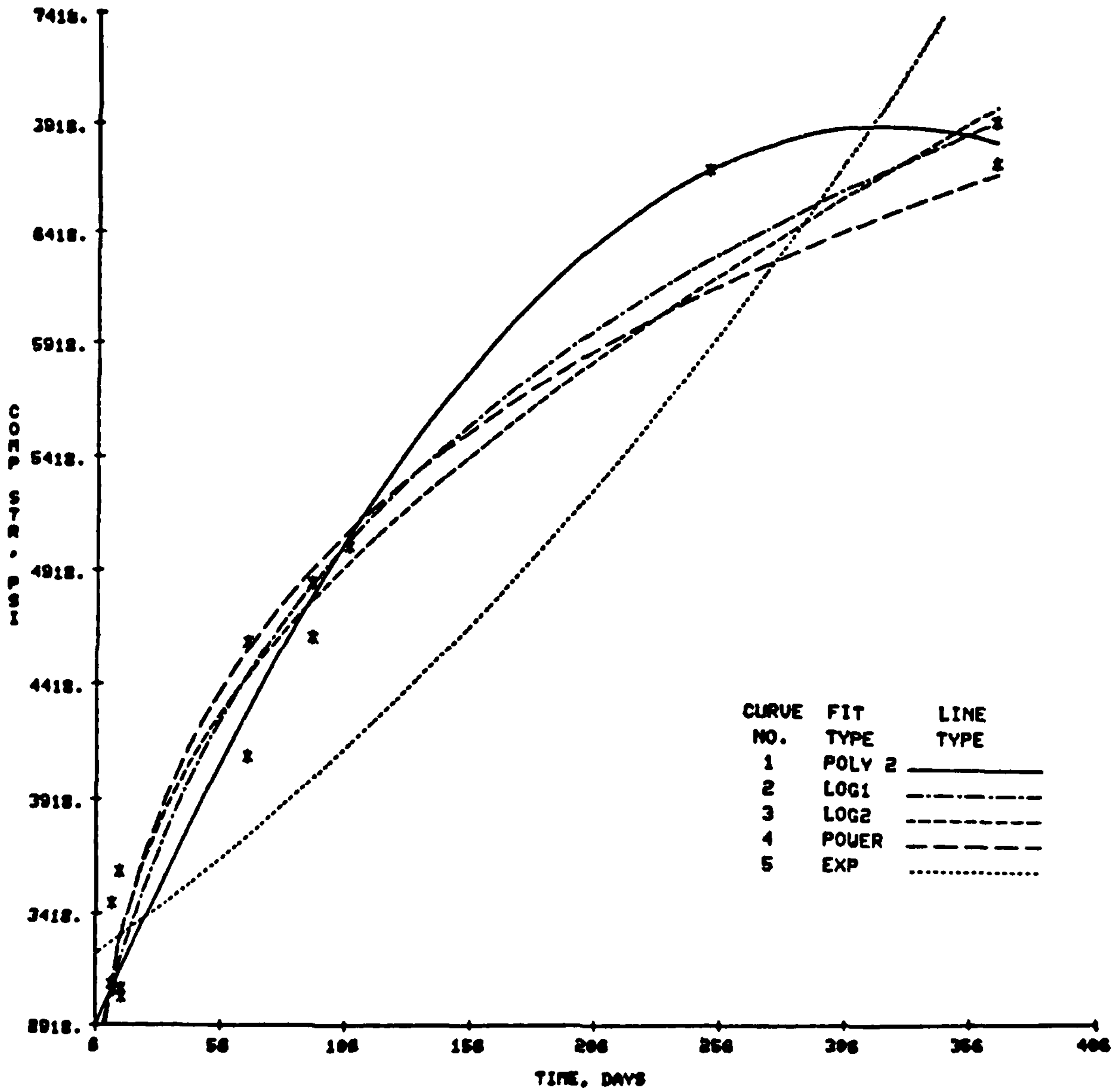

Figure 1. Comparison of five curves generated by the CURVFIT program, all having correlation coefficients greater than 0.98. Series A, compressive strength, 6-in. cylinder.

Table 1

Components and Proportions of Expansive Salt-Saturated Concrete (ESC)

Component[a]	% of total by mass	% of total solids, by mass	Actual batch weight, lbs[c]
Class H cement	9.03	9.66	1822.5
Chem CompIII	6.02	6.45	1215.0
Cal-Seal	1.80	1.94	364.5
Class C fly ash	5.10	5.44	1026.0
Fine aggregate[b]	34.11	36.50	6823.6
Coarse aggregate[b]	34.58	37.00	6903.6
NaCl	2.50	2.65	499.5
Defoaming agent	0.21	0.24	42.9
Na citrate	0.11	0.12	0.164
Water (iced)	6.60	--	1461.7
Total	100.06	100.00	

a) Sources of components and additional information on selection and use are given by Wakeley and Walley (1986).

b) Aggregate total is 61.1% by volume of fresh concrete.

c) Batch prepared for Test Series A of the SSSPT.

Table 2
Number of Specimens Prepared During Field Placements for Laboratory Testing

Size, in.	Type	Test Series A	Test Series B
3 by 6	Steel cylinder	24	0
4 by 8	Plastic cylinder	48	63
4 by 8	Air-shipped, plastic cylinder	0	9
6 by 12	Steel cylinder	6	19
6 by 12	Plastic cylinder	16	26
8 by 16	Creep specimens	0	8
3 by 3 by 10	Prism, unrestrained	3	2
3 by 3 by 10	Prism, restrained, 3/16" rod	3	2
3 by 3 by 10	Prism, restrained, 1/4" rod	0	2
3 by 3 by 10	Prism, restrained, 3/8" rod	3	2
3 by 3 by 10	Prism, restrained, 1/2" rod	3	2
--	Other	0	6

Table 3

Curves Used by CURVFIT

EXPONENTIAL:	Y=A*EXP(B*(X+X1))-Y1
POWER:	Y=A*(X+X1)**B-Y1
COMMON LOG(LOG1):	Y=A1+A2*LOG(X+X1)+A3*(LOG(X+X1))**2
COMMON LOG(LOG2):	Y=A1+A2*(X+X1)+A3*LOG(X+X1)
NATURAL LOG(LG1):	Y=A+B*LN(X+X1)
POLY 1:	Y=A1+A2*(X+X1) [Straight Line]
POLY 2:	Y=A1+A2*(X+X1)+A3*(X+X1)**2
POLY 3:	Y=A1+A2*(X+X1)+A3*(X+X1)**2+A4*(X+X1)**3
HYPERBOLA:	Y+A+B/(X+X1)

where: Y - denotes the predicted value calculated from an input value of X.

A1, A2, A3, A4, X1, Y1 - are coefficients calculated by the program.

* - indicates multiplication.

** - indicates raised to the power of.

APPENDIX A

COMPRESSIVE STRENGTH VS. TIME

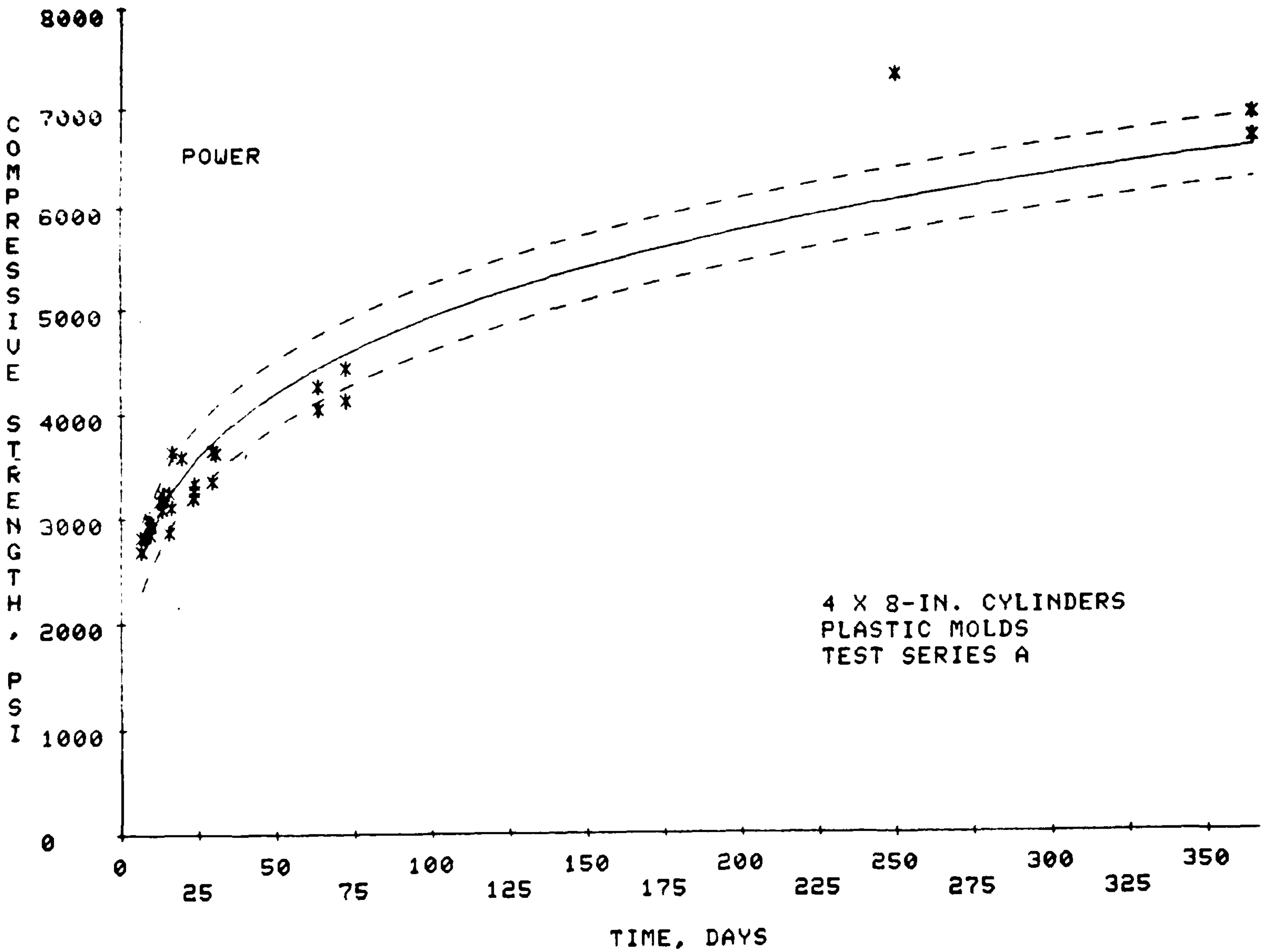

Figure A1. Compressive Strength of 4 X 8-in. Cylinders, Plastic Molds, Test Series A.

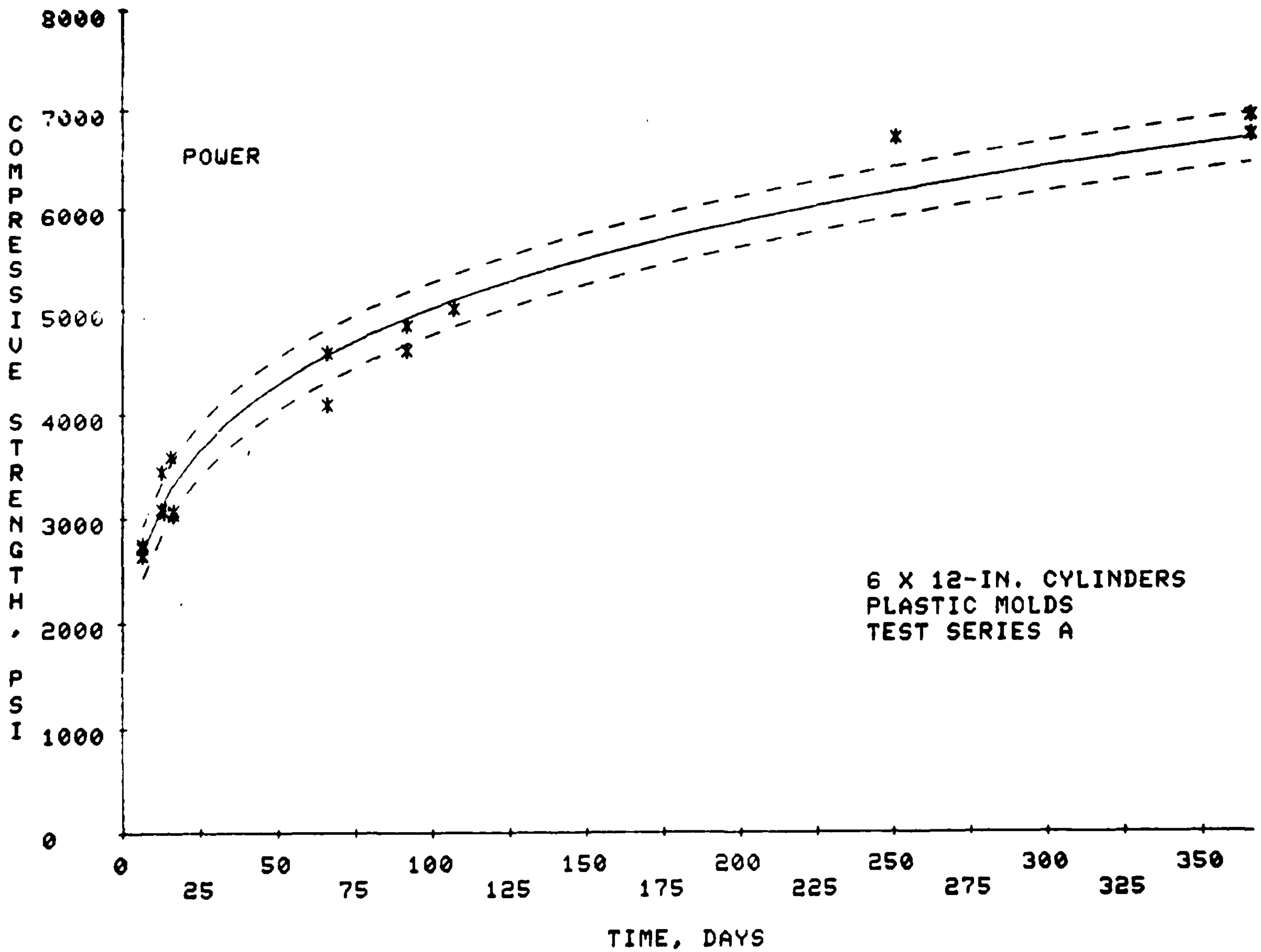

Figure A2. Compressive Strength of 6 X 12-in. Cylinders, Plastic Molds, Test Series A.

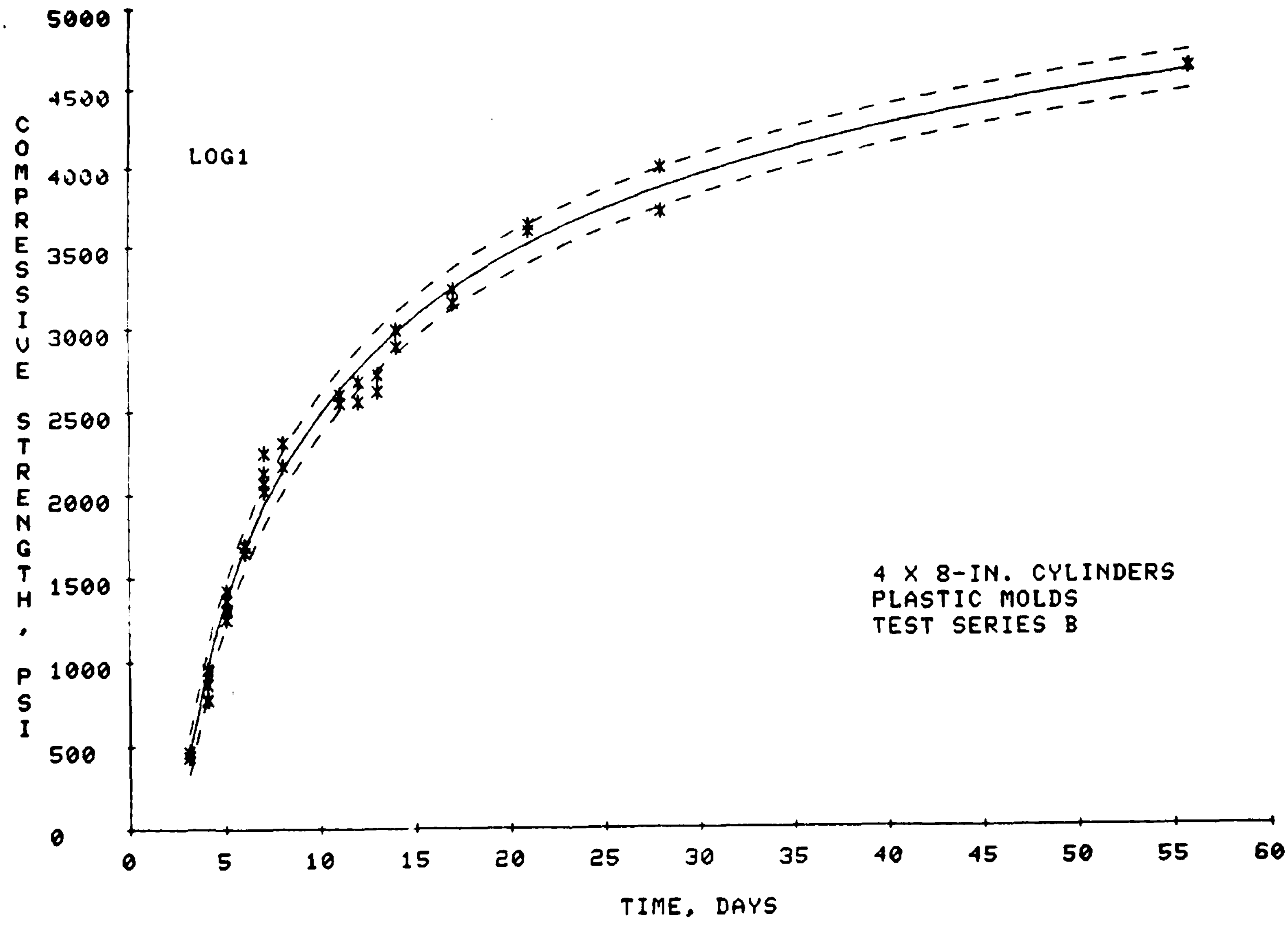

Figure A3. Compressive Strength of 4 X 8-in. Cylinders, Plastic Molds, Test Series B.

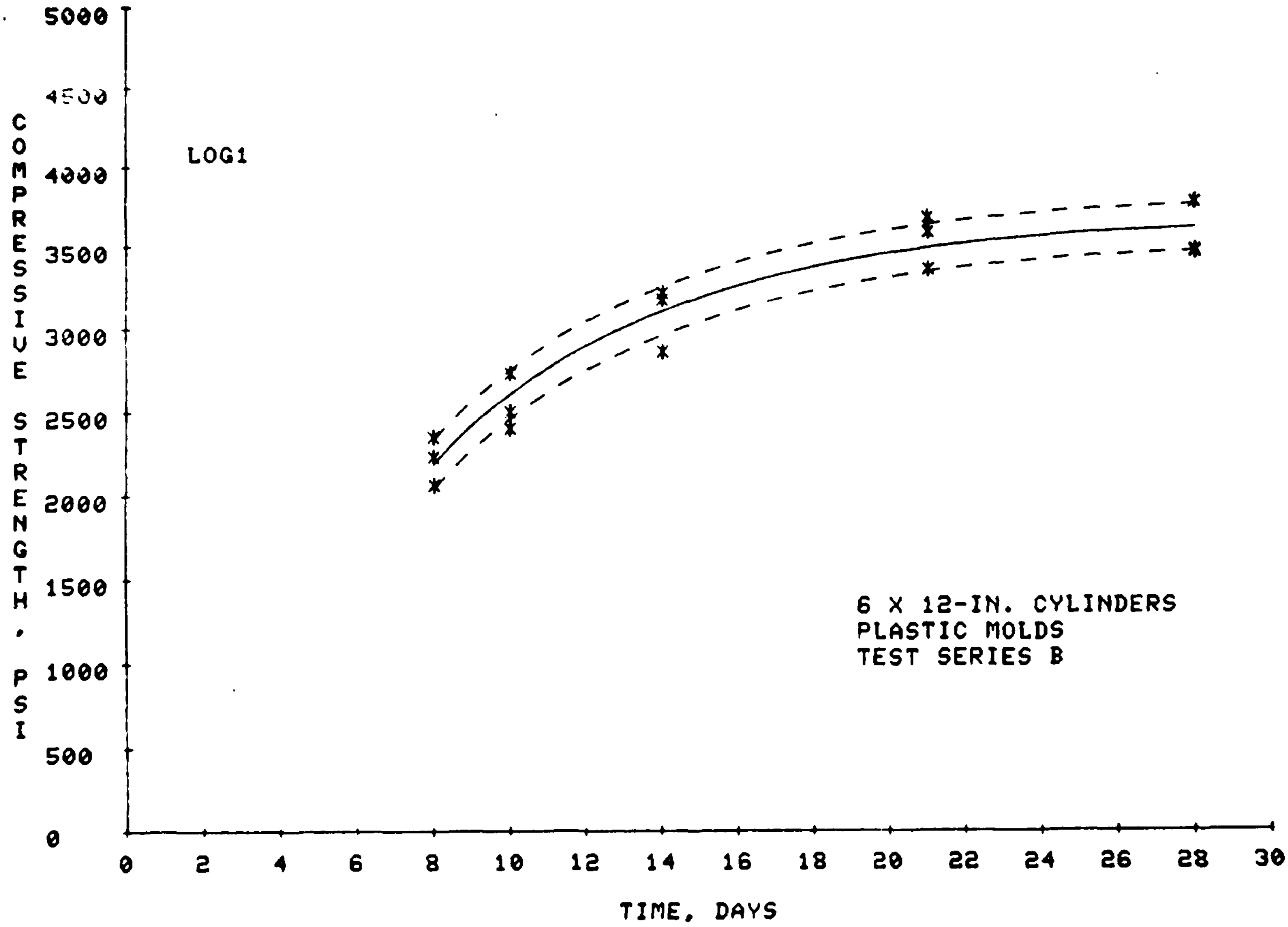

Figure A4. Compressive Strength of 6 X 12-in. Cylinders, Plastic Molds, Test Series B.

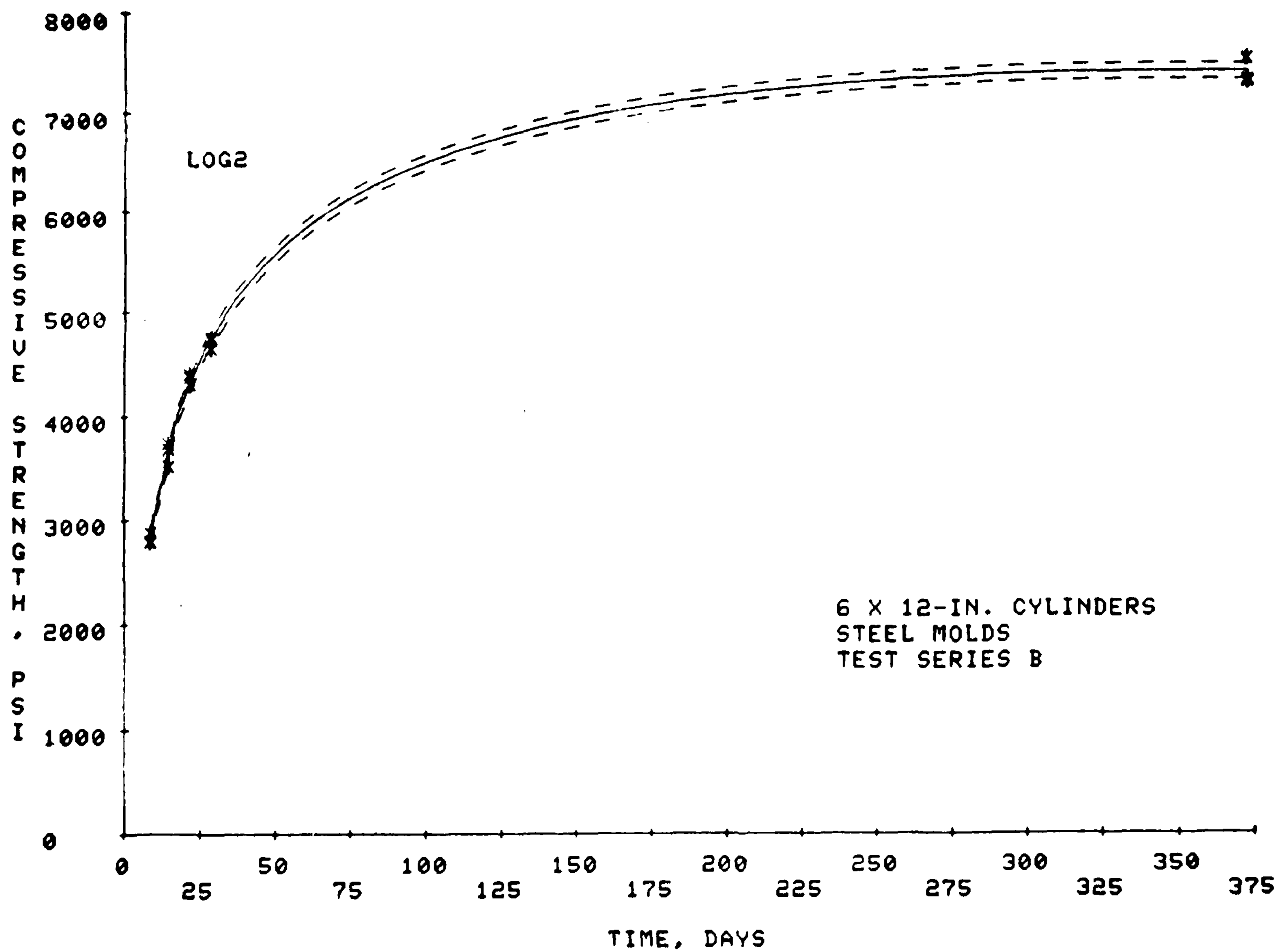

Figure A5. Compressive Strength of 6 X 12-in. Cylinders, Steel Molds, Test Series B.

APPENDIX B

TABULAR DATA OF COMPRESSIVE STRENGTH

Table B1. Data from Compressive Strength of 4-by-8-in. Cylinders, Plastic Molds, Test Series A

Age When Tested, Days	Compressive Strength, psi	Average
6	2,700	
6	2,830	2,770
7	2,840	
9	2,860	
9	3,020	
9	2,940	
9	2,980	2,950
12	3,180	
13	3,180	
13	3,100	
13	3,250	3,180
15	3,260	
15	2,880	3,070
16	3,120	
16	3,650	3,390
19	3,600	
23	3,280	
23	3,350	
23	3,210	3,280
29	3,370	
29	3,660	3,520
30	3,640	
63	4,280	
63	4,060	4,170
72	4,450	
72	4,140	4,300
251	7,320	
366	6,920	
366	6,680	6,800

Table B2. Data from Compressive Strength of 6-by-12-in. Cylinders, Plastic Molds, Test Series A

Age When Tested, Days	Uniaxial Stress, psi	Average
6	2,650	
6	2,760	
6	2,730	2,710
12	3,460	
12	3,100	3,280
13	3,070	
15	3,600	
16	3,080	
16	3,040	3,060
66	4,100	
66	4,600	4,350
92	4,860	
92	4,620	4,740
107	5,020	
251	6,720	
366	6,760	
366	6,950	6,860

Table B3. Data from Compressive Strength of 4-by-8-in. Cylinders, Plastic Molds, Test Series B

Age When Tested, Days	Uniaxial Stress, psi	Average
3	470	
3	440	460
4	780	
4	960	
4	870	870
5	1,260	
5	1,310	
5	1,370	
5	1,430	1,340
6	1,660	
6	1,700	1,680
7	2,260	
7	2,140	
7	2,080	
7	2,030	2,130
8	2,320	
8	2,180	2,250
11	2,610	
11	2,560	2,590
12	2,690	
12	2,570	2,630
13	2,730	
13	2,630	2,680
14	3,000	
14	2,900	2,950
17	3,240	
17	3,160	3,200
21	3,640	
21	3,600	3,620
28	3,720	
28	4,000	3,860
56	4,620	

Table B4. Data from Compressive Strength of 6-by-12-in. Cylinders, Plastic Molds, Test Series B

Age When Tested, Days	Uniaxial Stress, psi	Average
8	2,240	
8	2,700	
8	2,360	2,430
10	2,510	
10	2,740	
10	2,410	2,550
14	3,180	
14	2,870	
14	3,220	3,090
21	3,590	
21	3,360	
21	3,680	3,540
28	3,780	
28	3,470	
28	3,480	3,580

Table B5. Data from Compressive Strength of 6-by-12-in. Cylinders, Steel Molds, Test Series B

Age When Tested, Days	Uniaxial Stress, psi	Average
8	2,890	
8	2,800	
8	2,810	2,830
14	3,750	
14	3,530	
14	3,700	3,660
21	4,390	
21	4,420	
21	4,320	4,380
28	4,760	
28	4,670	
28	4,780	4,740
374	7,340	
374	7,550	
374	7,320	7,400

APPENDIX C

STATIC MODULUS OF ELASTICITY VS. TIME

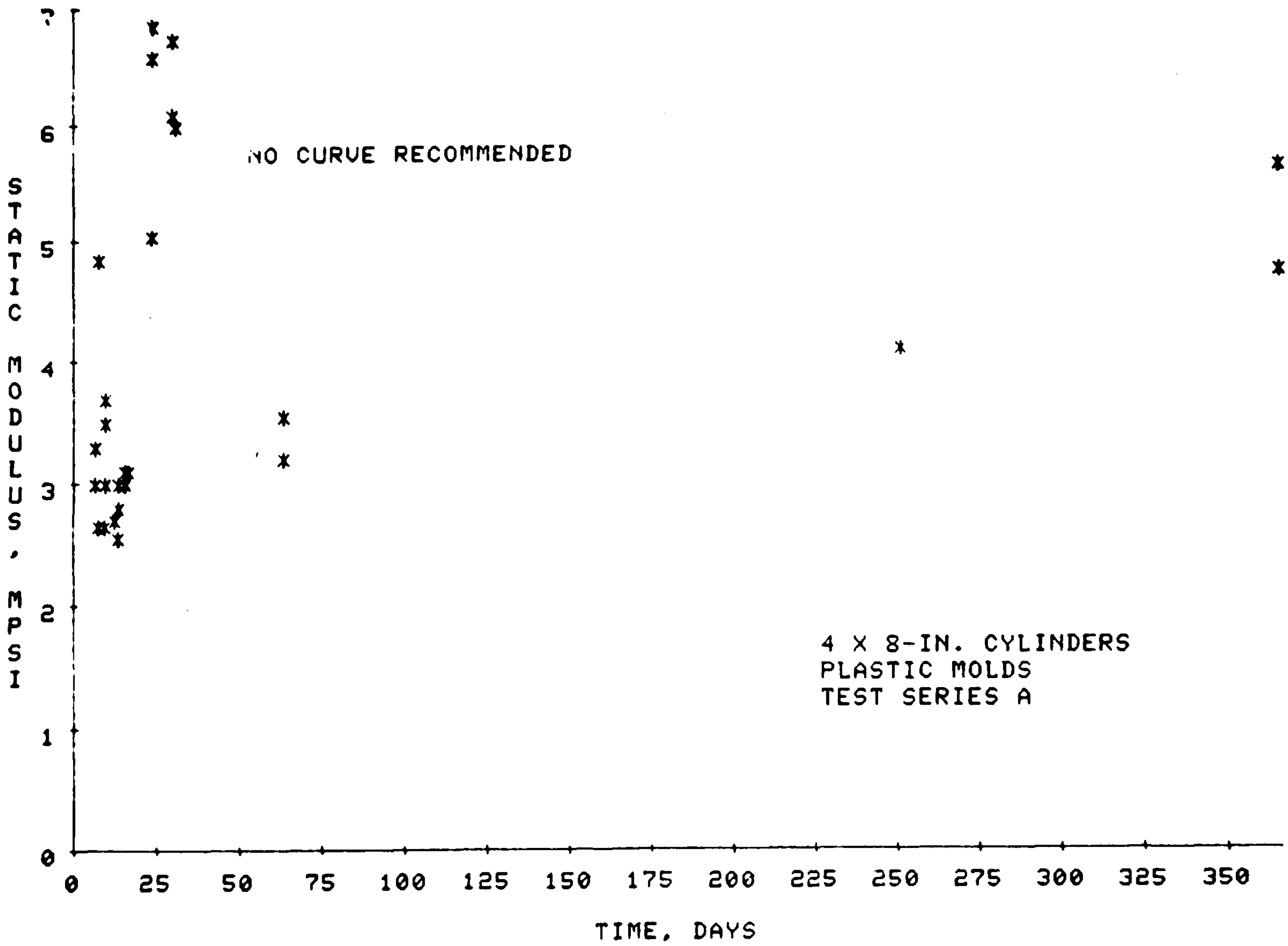

Figure C1. Static Modulus of Elasticity, 4 X 8-in. Cylinders, Plastic Molds, Test Series A.

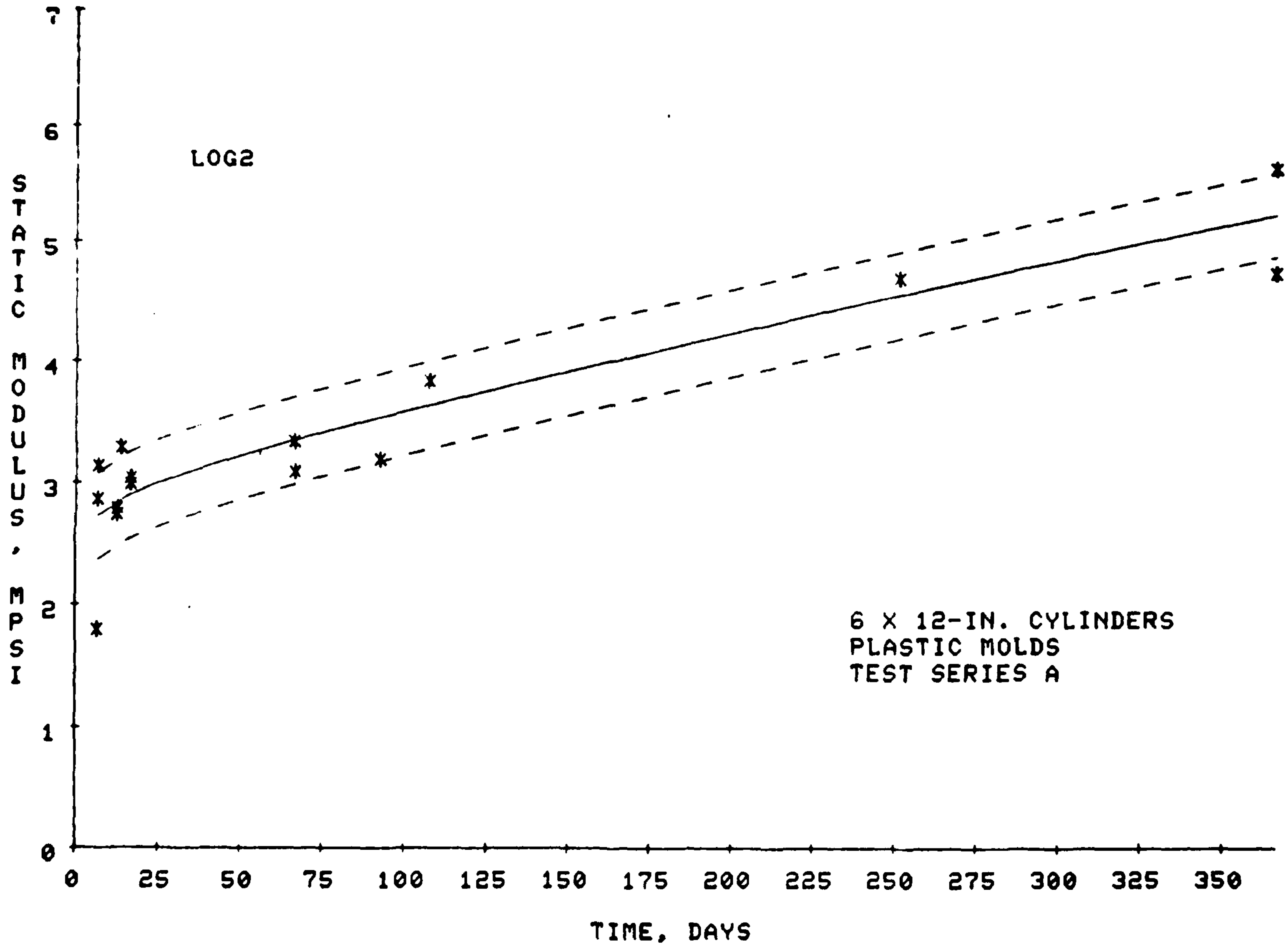

Figure C2. Static Modulus of Elasticity, 6 X 12-in. Cylinders, Plastic Molds, Test Series A.

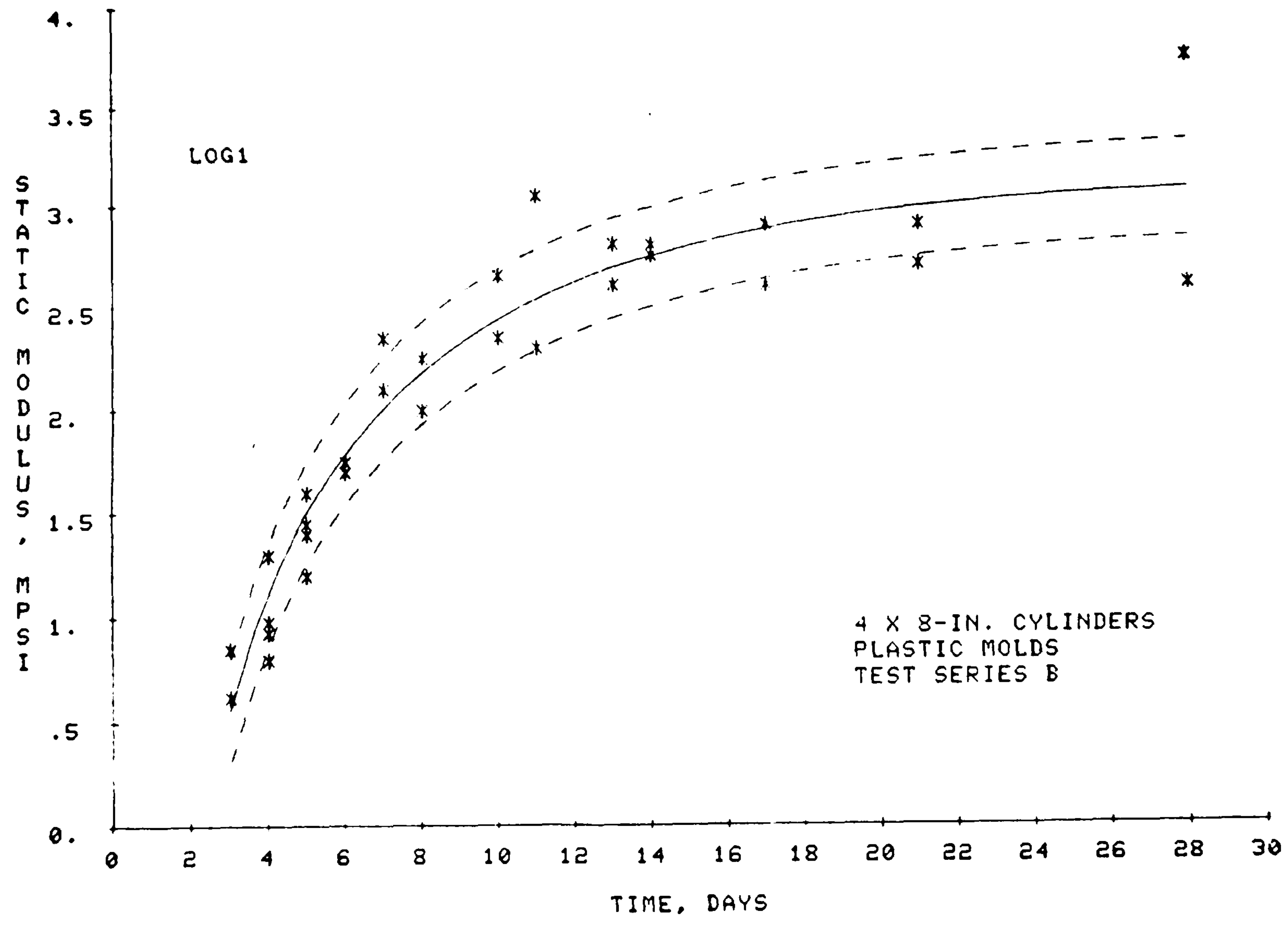

Figure C3. Static Modulus of Elasticity, 4 X 8-in. Cylinders, Plastic Molds, Test Series B.

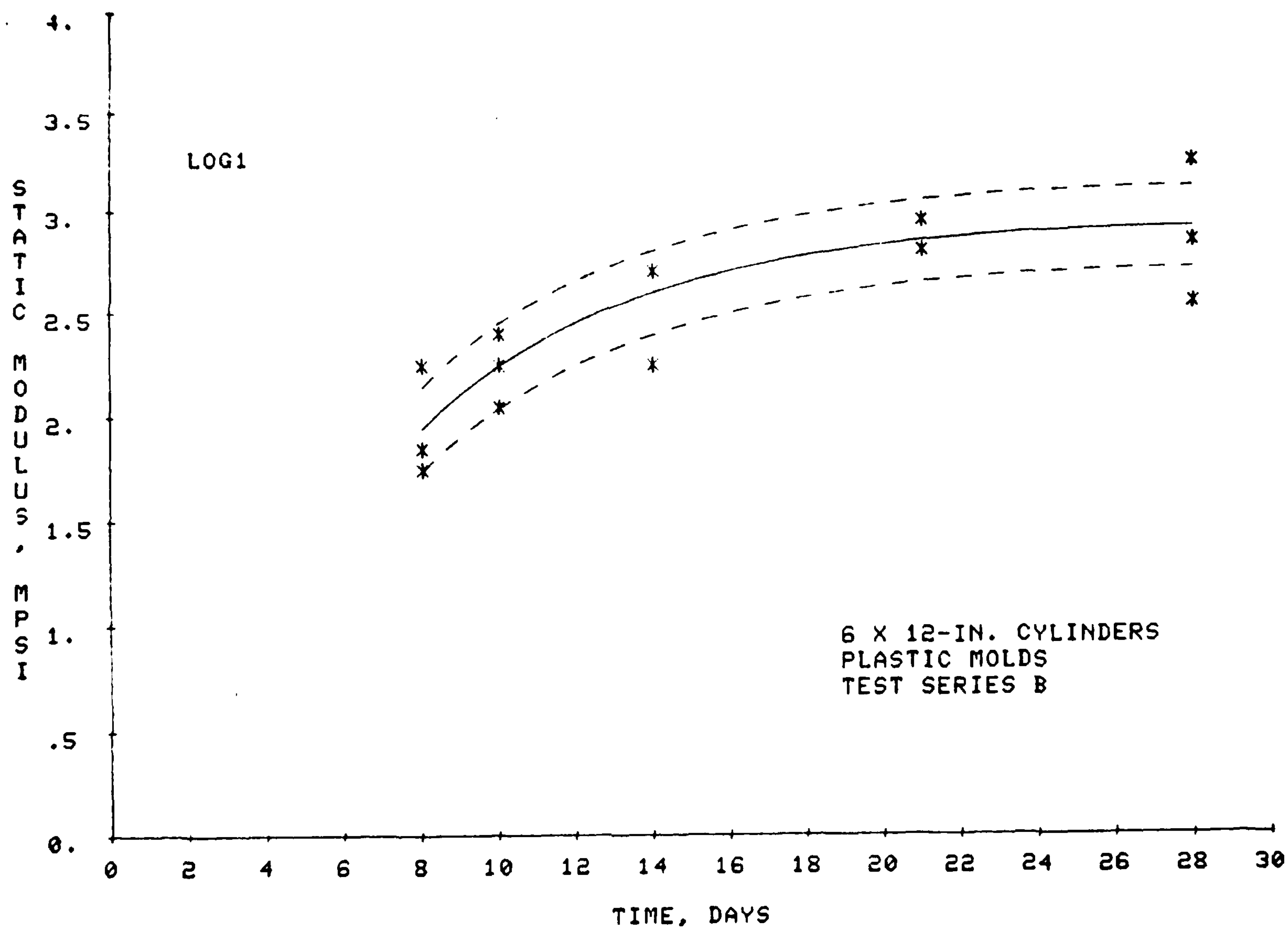

Figure C4. Static Modulus po Elasticity, 6 X 12-in. Cylinders, Plastic Molds, Test Series B.

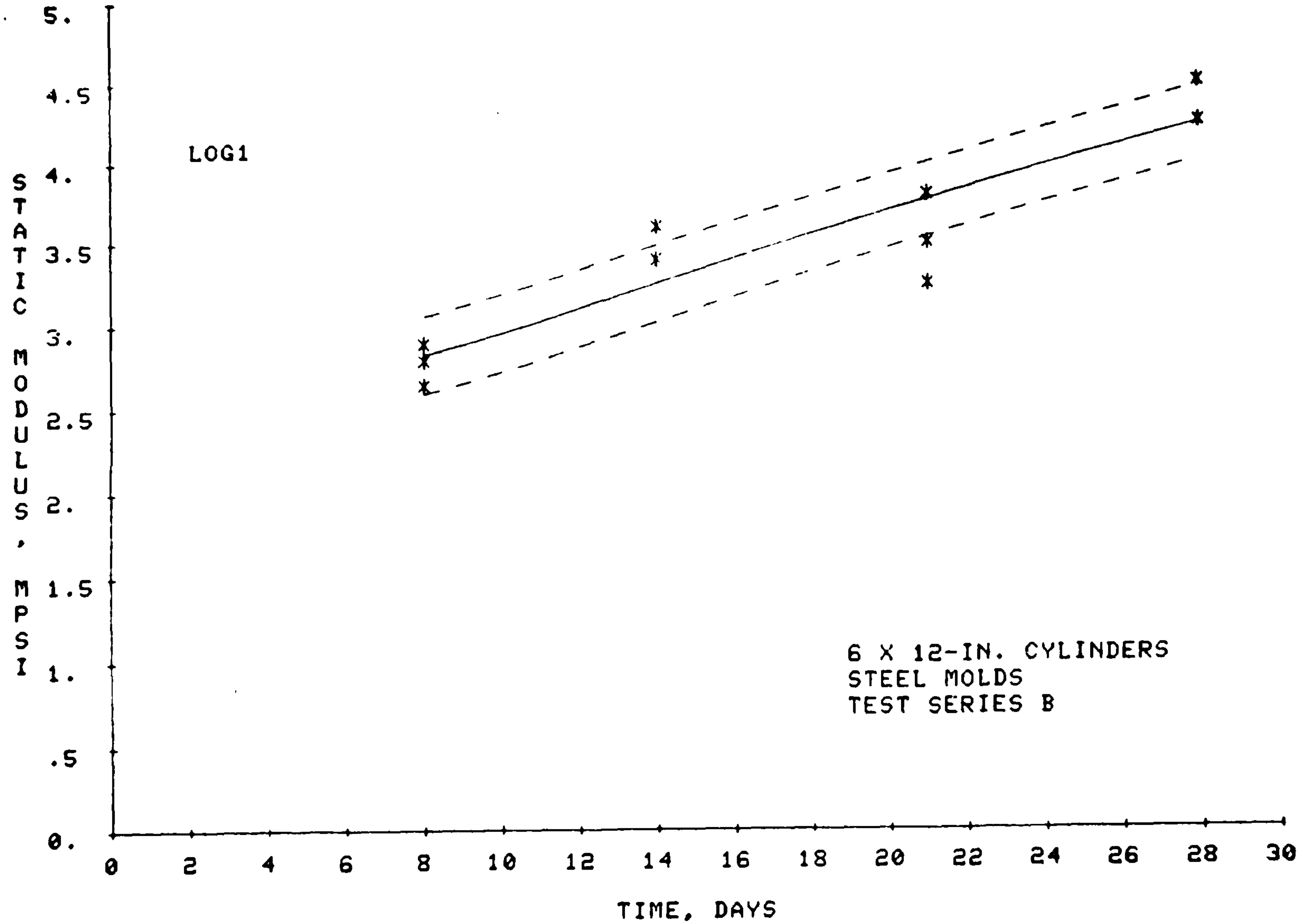

Figure C5. Static Modulus of Elasticity, 6 X 12-in. Cylinders, Steel Molds, Test Series B.

APPENDIX D

TABULAR DATA OF STATIC MODULUS OF ELASTICITY

Table D1. Data from Static Modulus of 4-by-8-in. Cylinders, Plastic Molds, Test Series A

Age When Tested, Days	$E \times 10^6$ psi	Average
6	3.30	
6	3.00	3.15
7	4.85	
7	2.65	3.75
9	2.65	
9	3.50	
9	3.70	
9	3.00	3.21
12	2.70	
13	2.55	
13	2.80	
13	3.00	2.78
15	3.10	
15	3.00	3.05
16	3.10	
23	5.05	
23	6.60	
23	6.87	6.15
29	6.75	
29	6.10	6.43
30	6.00	
63	3.55	
63	3.20	3.38
251	4.10	
366	5.65	
366	4.75	5.20

Table D2. Data from Static Modulus of 6-by-12-in. Cylinders, Plastic Molds, Test Series A

Age When Tested, Days	E x 10^6 psi	Average
6	1.80	
6	2.90	
6	3.15	
12	2.75	
12	2.80	2.78
13	3.30	
16	3.00	
16	3.05	3.03
66	3.10	
66	3.35	3.23
92	3.20	
107	3.85	
251	4.70	
366	4.20	
366	4.70	4.45

Table D3. Data from Static Modulus of 4-by-8-in. Cylinders, Plastic Molds, Test Series B

Age When Tested, Days	$E \times 10^6$ psi	Average
3	0.62	
3	0.85	0.74
4	0.80	
4	0.93	
4	1.30	
4	0.98	1.01
5	1.20	
5	1.40	
5	1.60	
5	1.45	1.41
6	1.75	
6	1.70	1.73
7	2.10	
7	2.35	2.22
8	2.25	
8	2.00	2.13
10	2.35	
10	2.65	2.50
11	3.05	
11	2.30	2.68
13	2.80	
13	2.60	2.70
14	2.75	
14	2.80	2.78
17	2.60	
17	2.90	2.75
21	2.90	
21	2.70	2.80
28	3.75	
28	2.60	3.18

Table D4. Data from Static Modulus of 6-by-12-in. Cylinders, Plastic Molds, Test Series B

Age When Tested, Days	E x 10^6 psi	Average
8	1.85	
8	1.75	
8	2.25	1.95
10	2.05	
10	2.40	
10	2.25	2.23
14	2.70	
14	2.25	
14	2.70	2.55
21	2.80	
21	2.95	
21	2.95	2.90
28	3.25	
28	2.55	
28	2.85	2.88

Table D5. Data from Static Modulus of 6-by-12-in. Cylinders, Steel Molds, Test Series B

Age When Tested, Days	E x 10^6 psi	Average
8	2.80	
8	2.65	
8	2.90	2.78
14	3.40	
14	3.60	3.50
21	3.50	
21	3.80	
21	3.25	3.52
28	4.50	
28	4.25	
28	4.25	4.33

APPENDIX E

POISSON'S RATIO VS. TIME

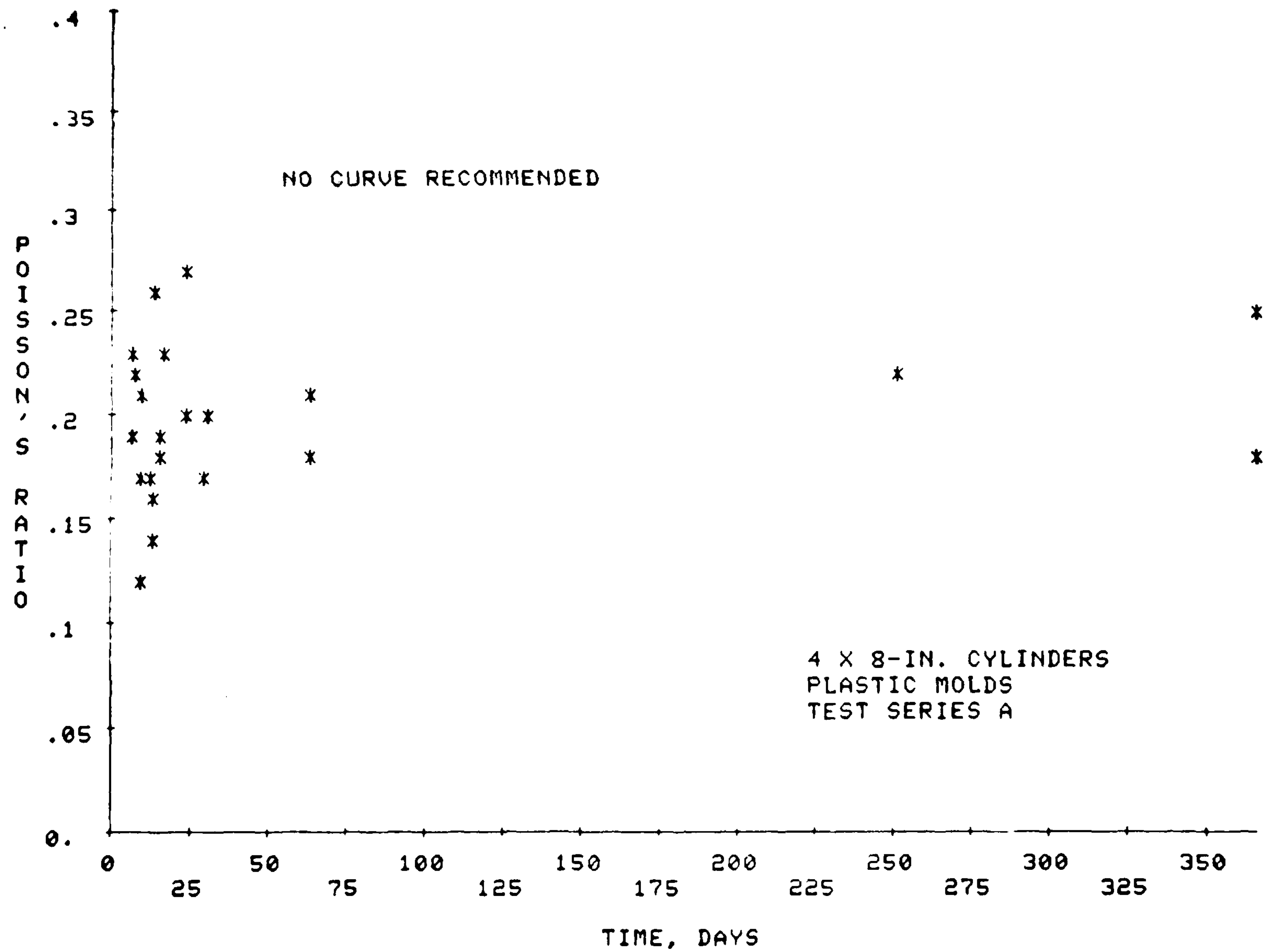

Figure E1. Poisson's Ratio, 4 X 8-in. Cylinders, Plastic Molds, Test Series A.

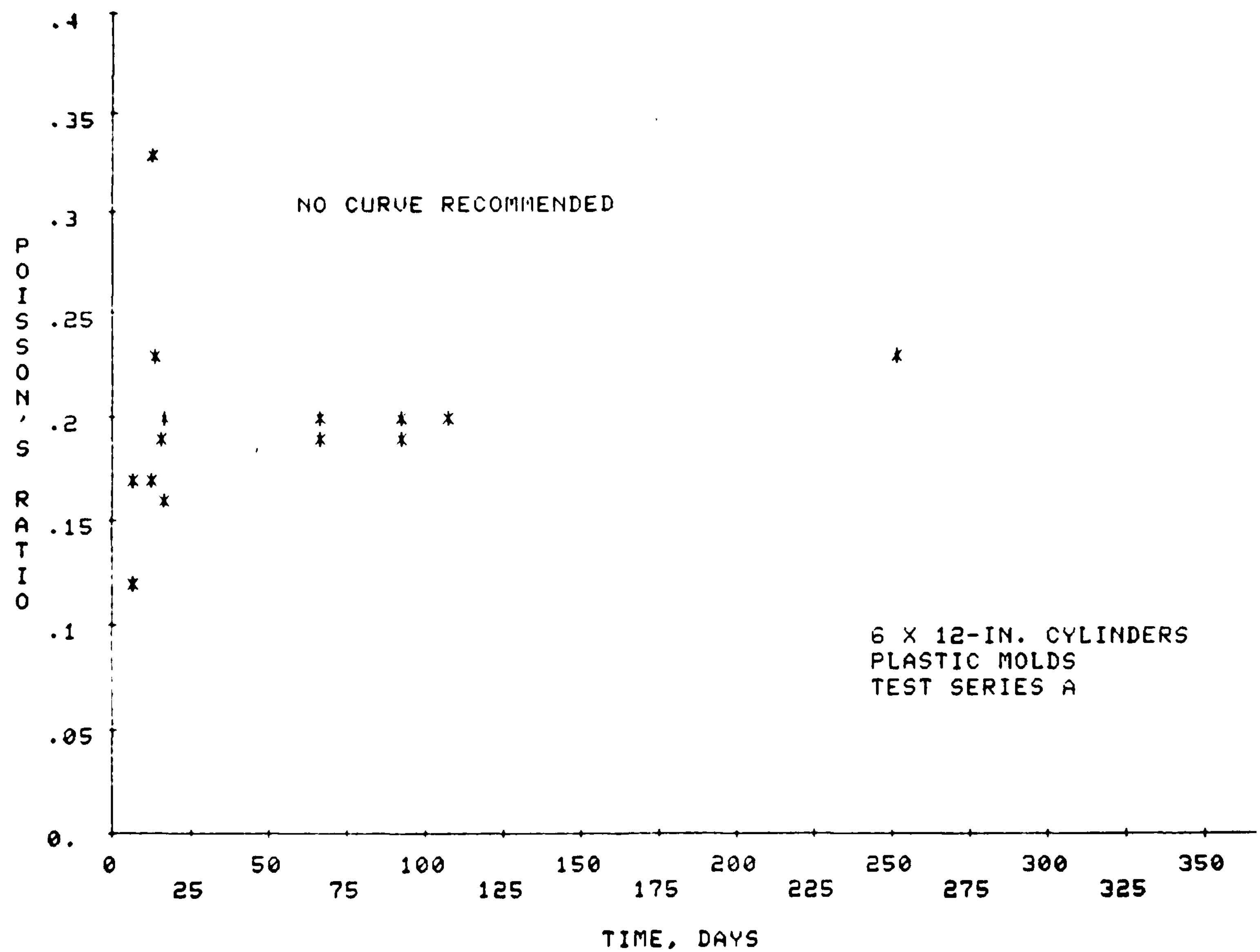

Figure E2. Poisson's Ratio, 6 X 12-in. Cylinders, Plastic Molds, Test Series A.

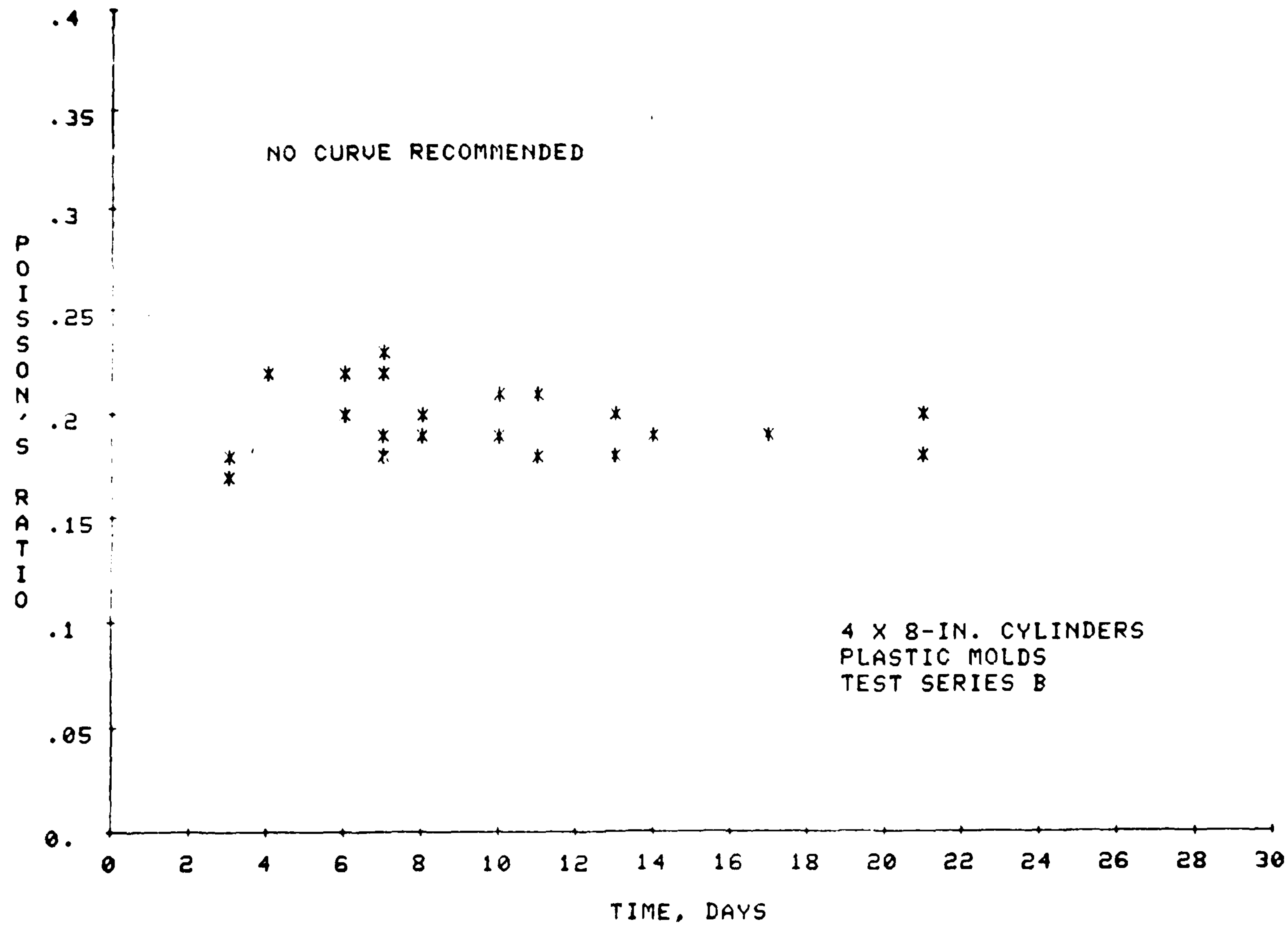

Figure E3. Poisson's Ratio, 4 X 8-in. Cylinders, Plastic Molds, Test Series B.

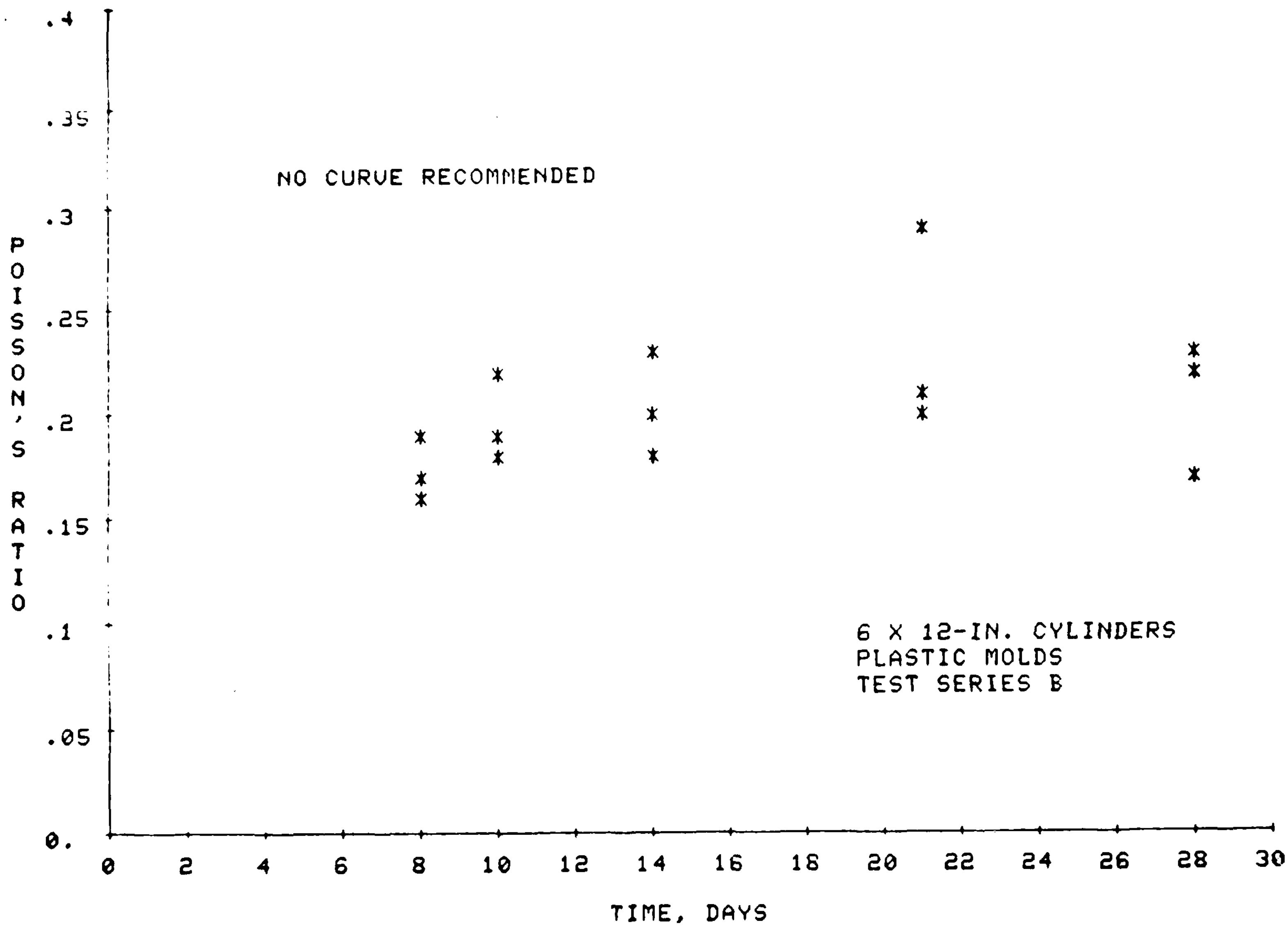

Figure E4. Poisson's Ratio, 6 X 12-in. Cylinders, Plastic Molds, Test Series B.

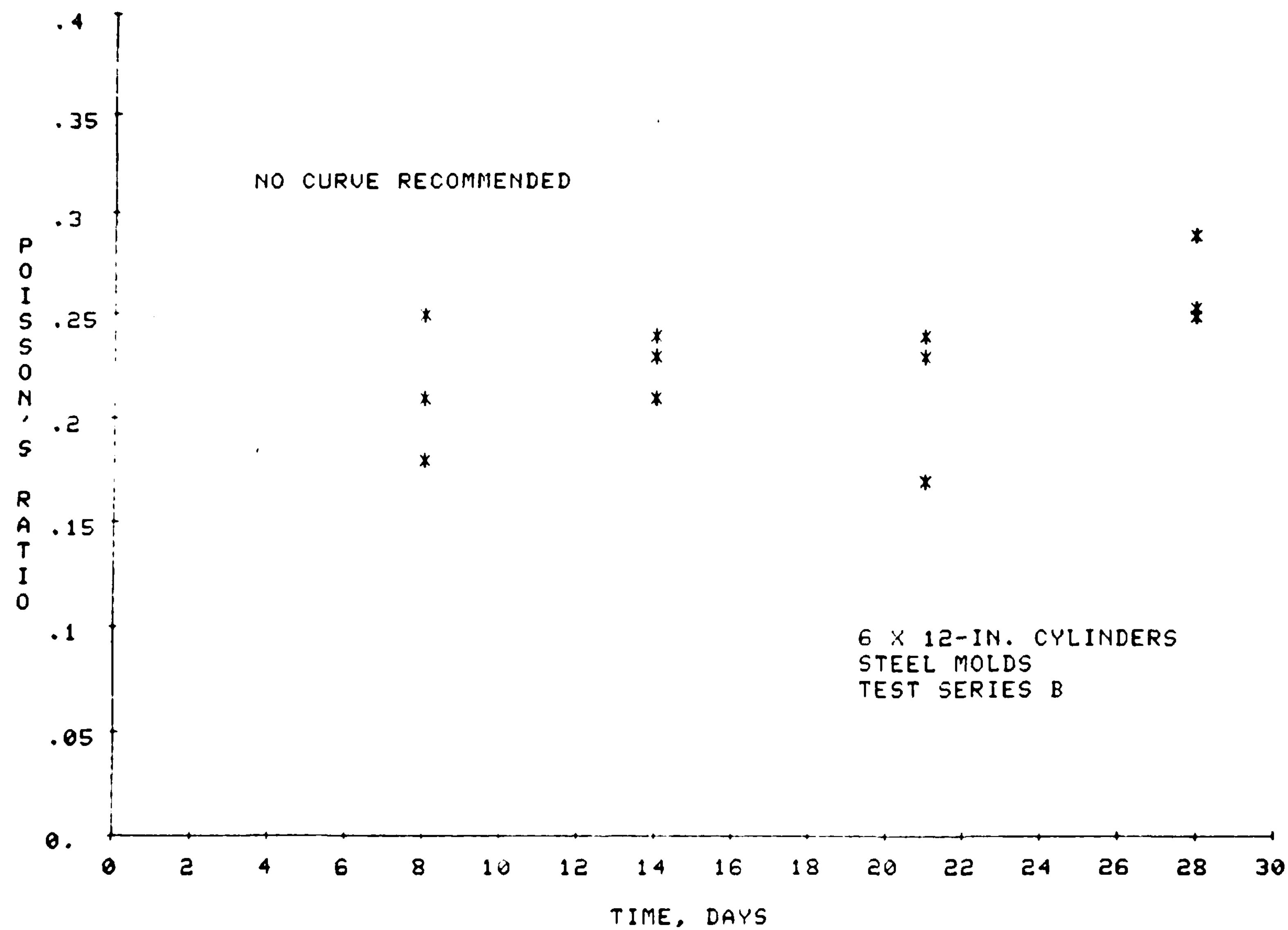

Figure E5. Poisson's Ratio, 6 X 12-in. Cylinders, Steel Molds, Test Series B.

APPENDIX F

TABULAR DATA OF POISSON'S RATIO

Table F1. Data from Poisson's Ratio of 4-by-8-in. Cylinders, Plastic Molds, Test Series A

Age When Tested, Days	Poisson's ratio	Average
6	0.23	
6	0.19	0.21
7	0.22	
9	0.12	
9	0.21	
9	0.17	
9	0.17	0.17
12	0.17	
13	0.16	
13	0.14	
13	0.26	0.19
15	0.18	
15	0.19	0.19
16	0.23	
23	0.20	
23	0.20	
23	0.27	0.22
29	0.17	
30	0.20	
63	0.18	
63	0.21	0.20
251	0.22	
366	0.25	
366	0.18	0.22

Table F2. Data from Poisson's Ratio of 6-by-12-in. Cylinders, Plastic Molds, Test Series A

Age When Tested, Days	Poisson's ratio	Average
6	0.17	
6	0.12	0.15
12	0.33	
12	0.17	0.25
13	0.23	
15	0.19	
16	0.20	
16	0.16	0.18
66	0.19	
66	0.20	0.20
92	0.20	
92	0.19	0.20
107	0.20	
251	0.23	
366	0.21	
366	0.25	0.23

Table F3. Data from Poisson's Ratio of 4-by-8-in. Cylinders, Plastic Molds, Test Series B

Age When Tested, Days	Poisson's ratio	Average
3	0.17	
3	0.18	0.18
4	0.22	
4	0.22	0.22
6	0.20	
6	0.22	0.21
7	0.18	
7	0.23	
7	0.22	
7	0.19	0.21
8	0.19	
8	0.20	0.20
10	0.19	
10	0.21	0.20
11	0.21	
11	0.18	0.20
13	0.20	
13	0.18	0.19
14	0.19	
14	0.19	0.19
17	0.19	
17	0.19	0.19
21	0.18	
21	0.20	0.19

Table F4. Data from Poisson's Ratio of 6-by-12-in. Cylinders, Plastic Molds, Test Series B

Age When Tested, Days	Poisson's ratio	Average
8	0.16	
8	0.19	
8	0.17	0.17
10	0.19	
10	0.18	
10	0.22	0.20
14	0.23	
14	0.18	
14	0.20	0.20
21	0.20	
21	0.21	
21	0.29	0.23
28	0.23	
28	0.17	
28	0.22	0.21

Table F5. Data from Poisson's Ratio of 6-by-12-in. Cylinders, Steel Molds, Test Series B

Age When Tested, Days	Poisson's ratio	Average
8	0.21	
8	0.18	
8	0.25	0.21
14	0.23	
14	0.24	
14	0.21	0.23
21	0.24	
21	0.23	
21	0.17	0.21
28	0.25	
28	0.25	
28	0.29	0.26

APPENDIX G

DYNAMIC MODULUS OF ELASTICITY VS. TIME

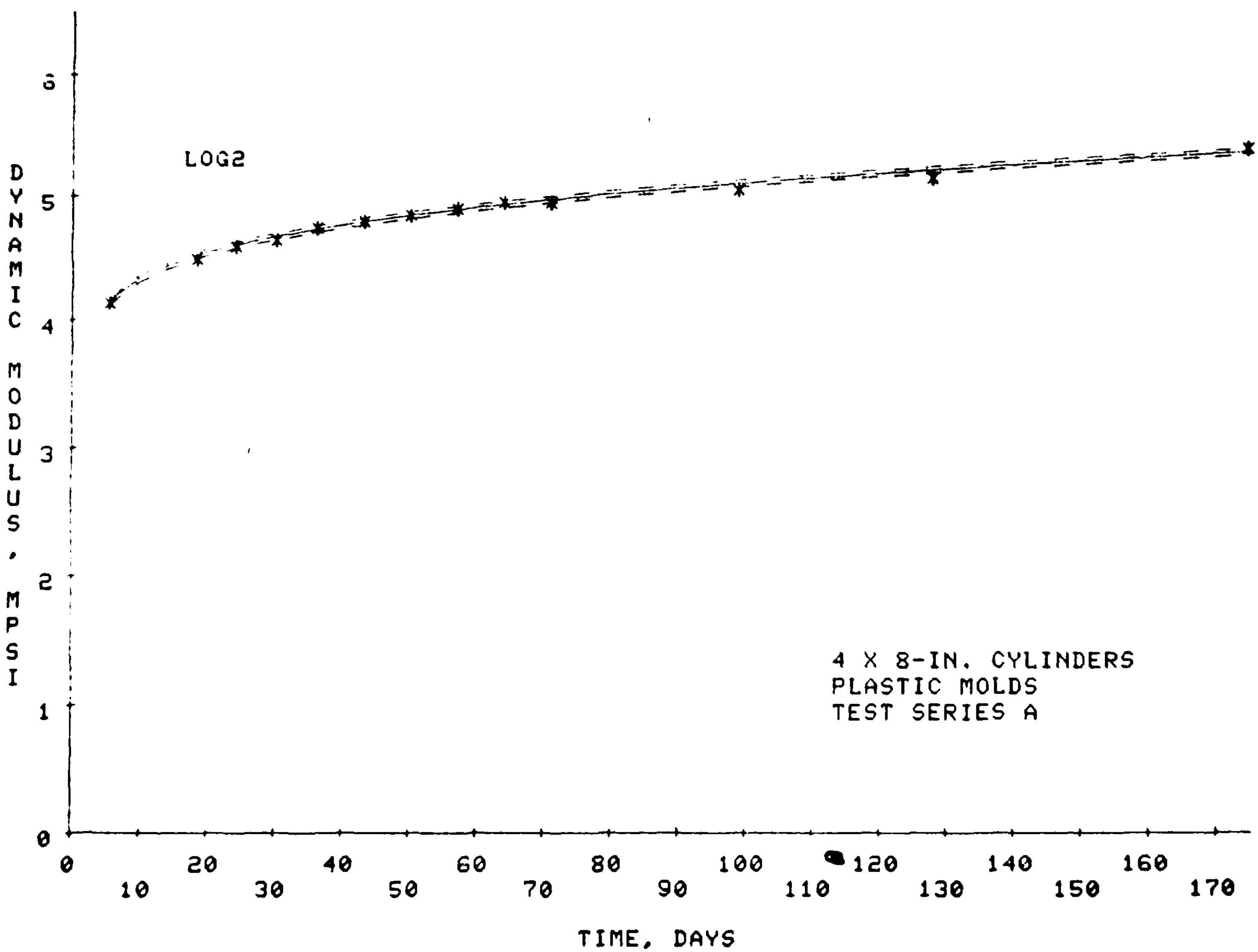

Figure G1. Dynamic Modulus of Elasticity, 4 X 8-in. Cylinders, Plastic Molds, Test Series A.

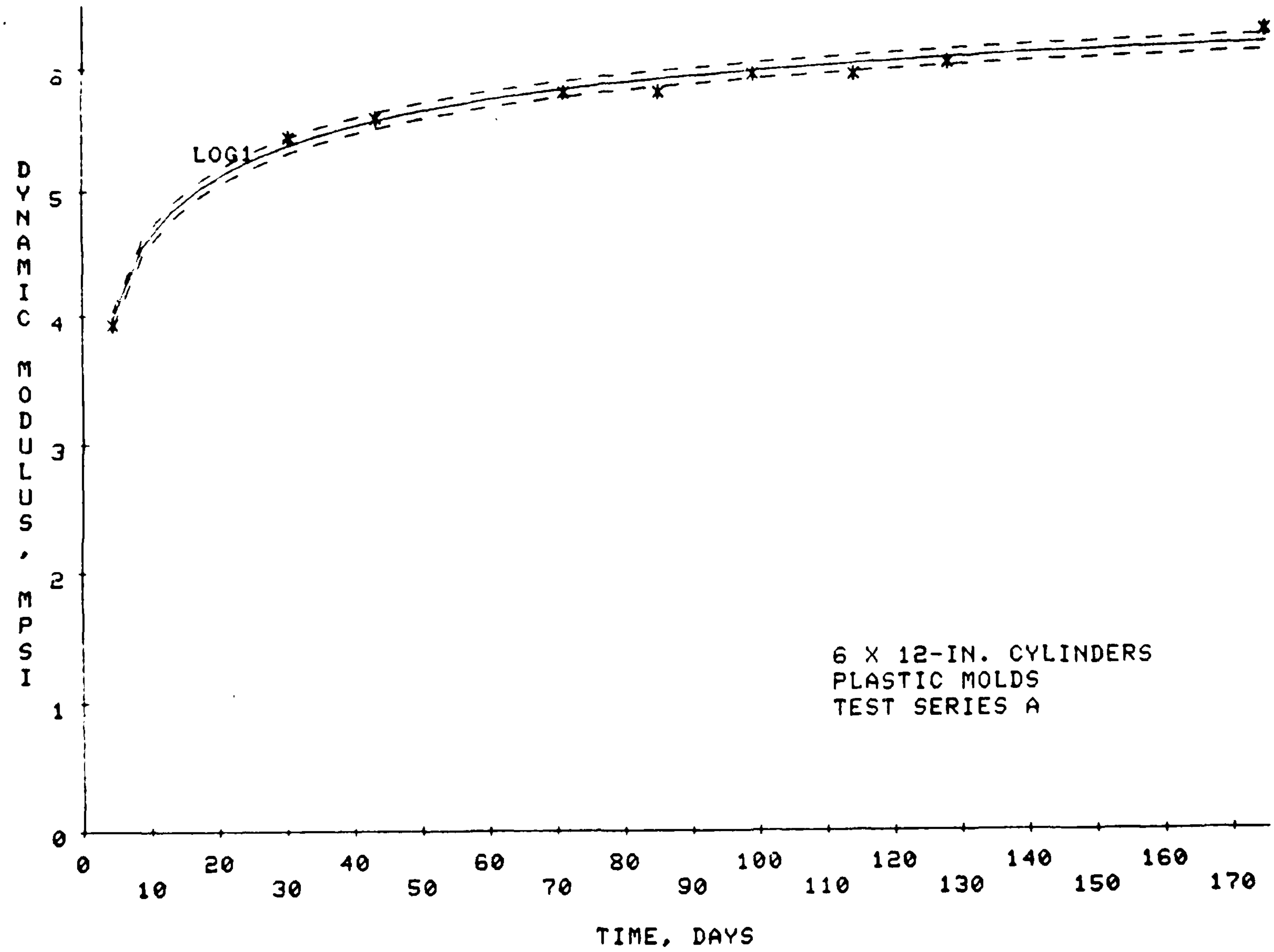

Figure G2. Dynamic Modulus of Elasticity, 6 X 12-in. Cylinders, Plastic Molds, Test Series A.

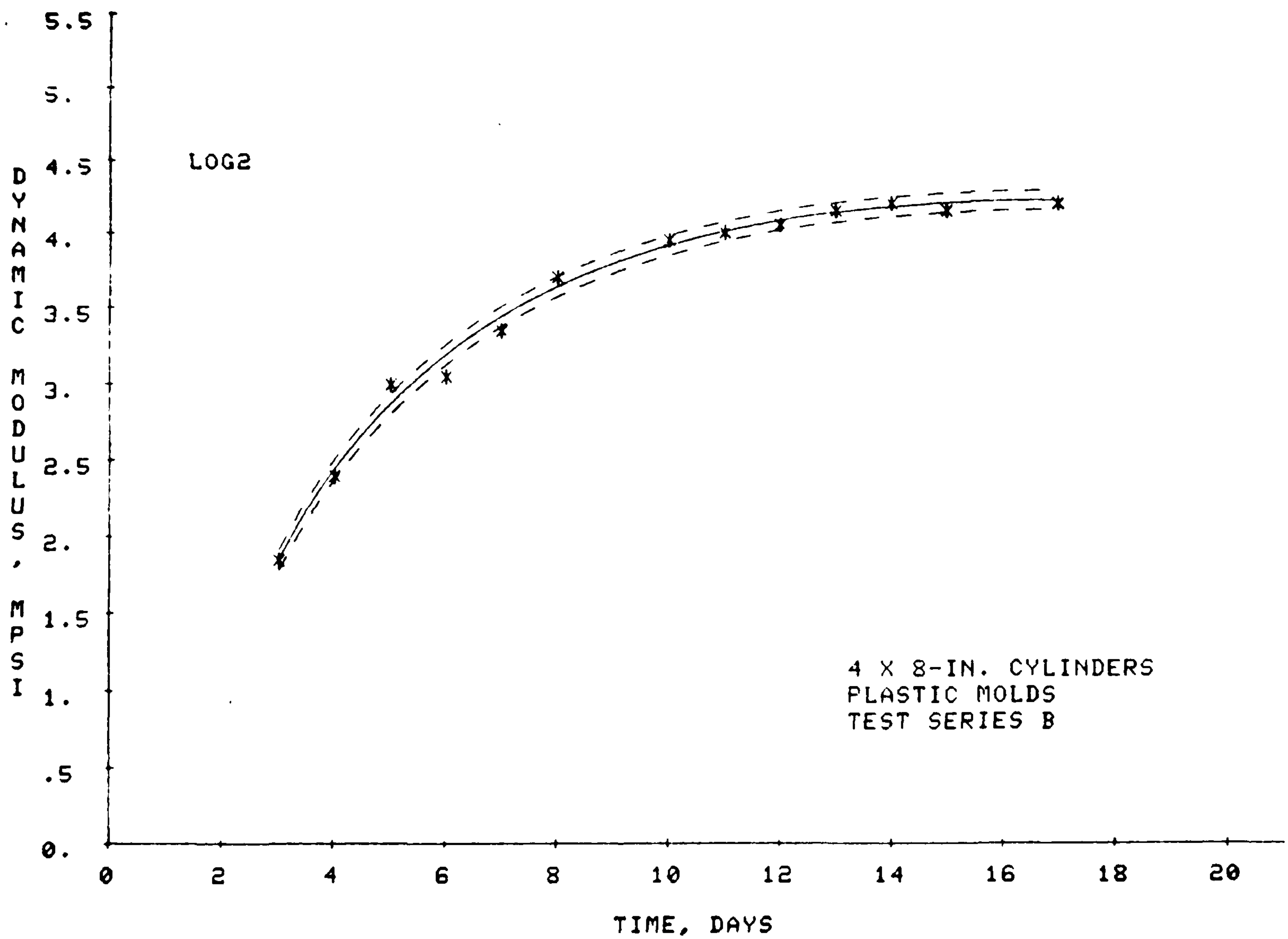

Figure G3. Dynamic Modulus of Elasticity, 4 X 8-in. Cylinders, Plastic Molds, Test Series B.

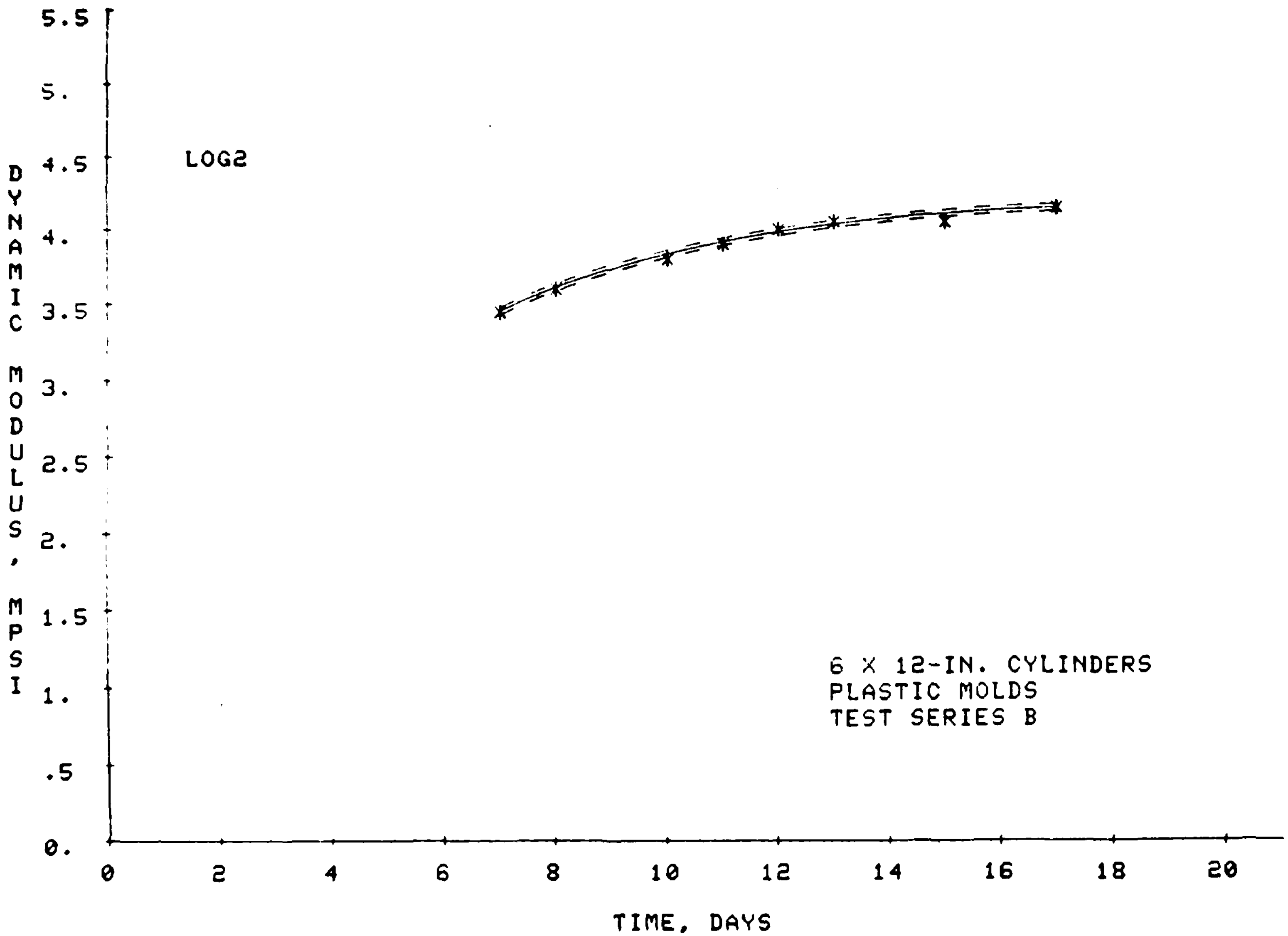

Figure G4. Dynamic Modulus of Elasticity, 6 X 12-in. Cylinders, Plastic Molds, Test Series B.

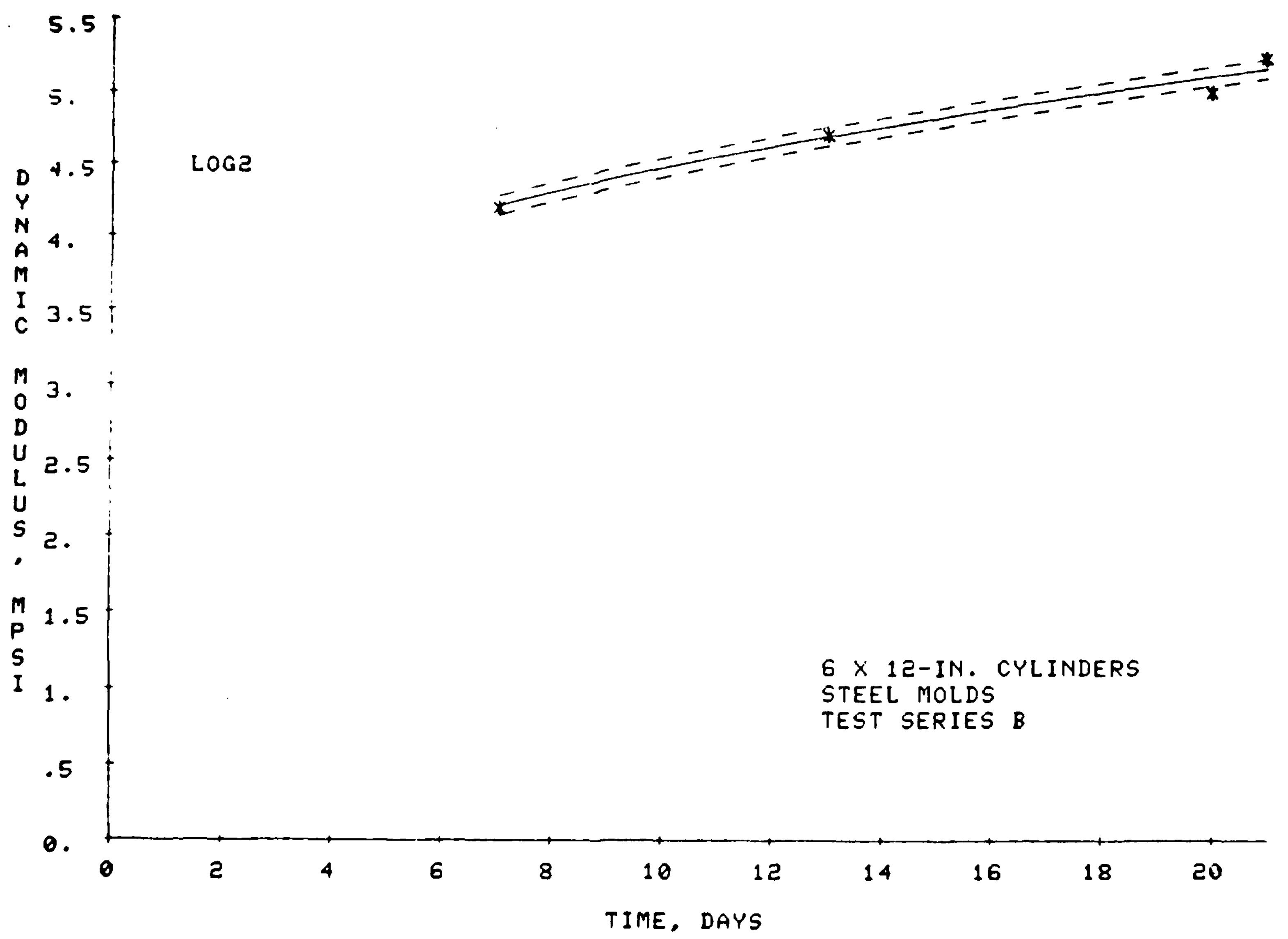

Figure G5. Dynamic Modulus of Elasticity, 6 X 12-in. Cylinders, Steel Molds, Test Series B.

APPENDIX H

TABULAR DATA OF DYNAMIC MODULUS OF ELASTICITY

Table H1. Data from Dynamic Modulus of 4-by-8-in. Cylinders, Plastic Molds, Tests Series A

Age When Tested, Days	$E \times 10^6$ psi
5	4.15
18	4.50
24	4.60
30	4.65
36	4.75
43	4.80
50	4.85
57	4.90
64	4.95
71	4.95
99	5.05
128	5.15
175	5.40

Table H2. Data from Dynamic Modulus of 6-by-12-in. Cylinders, Plastic Molds, Tests Series A

Age When Tested, Days	$E \times 10^6$ psi
4	3.95
30	5.45
43	5.60
71	5.80
85	5.80
99	5.95
114	5.95
128	6.05
175	6.30

Table H3. Data from Dynamic Modulus of 4-by-8-in. Cylinders, Plastic Molds, Tests Series B

Age When Tested, Days	$E \times 10^6$ psi
3	1.85
4	2.40
5	3.00
6	3.05
7	3.35
8	3.70
10	3.95
11	4.00
12	4.05
13	4.15
14	4.20
15	4.15
17	4.20

Table H4. Data from Dynamic Modulus of 6-by-12-in. Cylinders, Plastic Molds, Tests Series B

Age When Tested, Days	$E \times 10^6$ psi
7	3.45
8	3.60
10	3.80
11	3.90
12	4.00
13	4.05
15	4.05
17	4.15

Table H5. Data from Dynamic Modulus of 6-by-12-in. Cylinders, Steel Molds, Tests Series B

Age When Tested, Days	$E \times 10^6$ psi
7	4.20
13	4.70
20	5.01
21	5.25

APPENDIX I

LINEAR EXPANSION

Table I1. Data from Linear Expansion of Unrestrained Prisms, Test Series B

Age When Tested, Days	Expansion, %
2	0.160
4	0.303
7	0.352
14	0.365
21	0.370
28	0.371
60	0.369
88	0.367

Table I2. Data from Linear Expansion of Prisms with Standard Restraining Rods, Test Series B

Age When Tested, Days	Expansion, %
2	0.026
4	0.059
7	0.086
14	0.088
21	0.092
28	0.097
60	0.103
88	0.126

Table I3. Data from Linear Expansion of Prisms with 1/4-in. Restraining Rods, Test Series B

Age When Tested, Days	Expansion, %
2	0.016
4	0.044
7	0.059
14	0.061
21	0.063
28	0.063
60	0.062
88	0.063

Table I4. Data from Linear Expansion of Prisms with 3/8-in. Restraining Rods, Test Series B

Age When Tested, Days	Expansion, %
2	0.008
4	0.022
7	0.030
14	0.030
21	0.030
28	0.028
60	0.024
88	0.029

Table I5. Data from Linear Expansion of Prisms with 1/2-in. Restraining Rods, Test Series B

Age When Tested, Days	Expansion, %
2	0.006
4	0.015
7	0.019
14	0.019
21	0.020
28	0.021
60	0.020
88	0.022

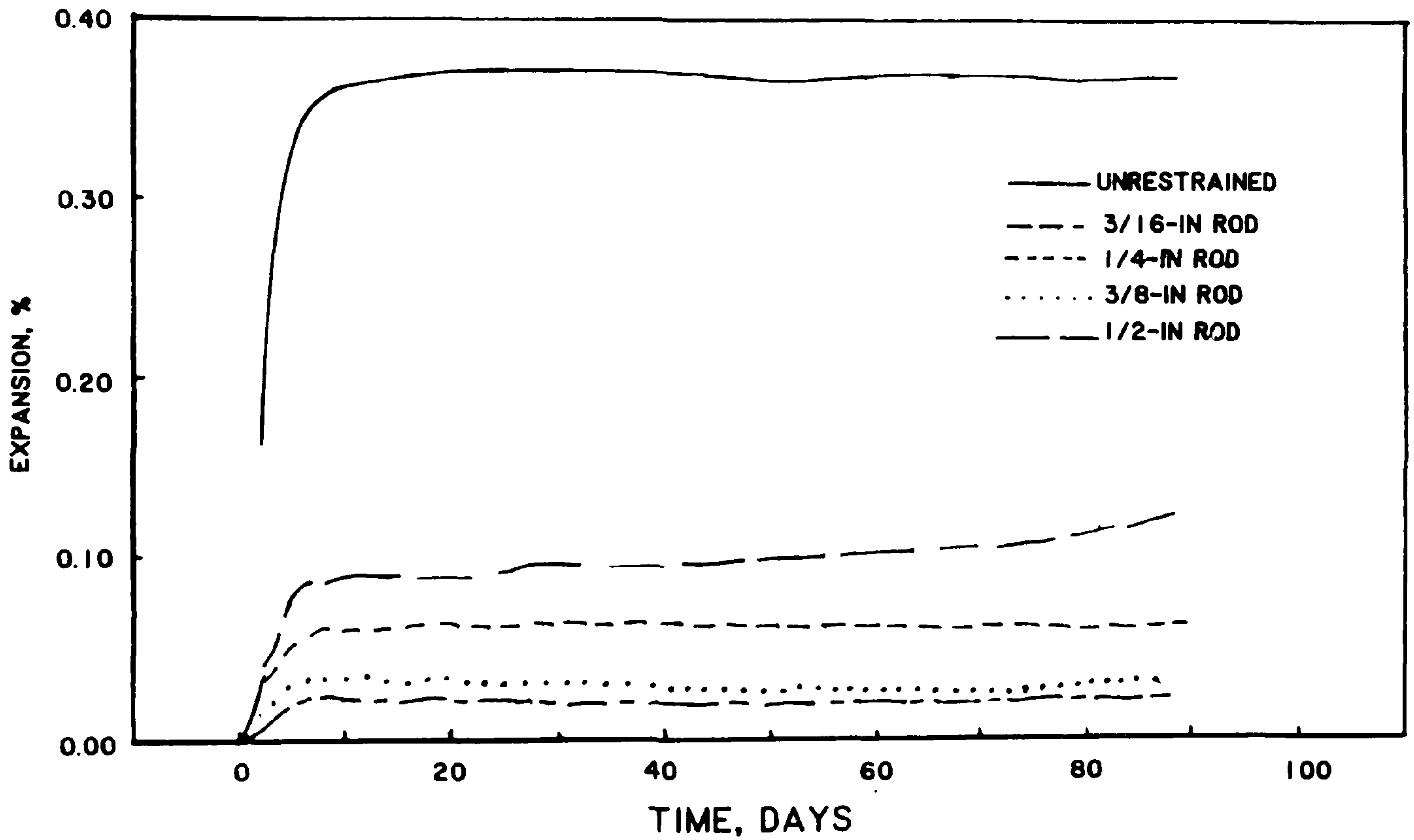

Figure I1. Expansion of Prisms with Restraining Rods of Different Diameters
Test Series B

APPENDIX J

EQUATIONS THAT MODEL THE TEST DATA

Table J1

EQUATIONS OF COMPRESSIVE STRENGTH VS. TIME

4 X 8-IN. CYLINDERS, PLASTIC MOLDS, TEST SERIES A

```
EXISTING DATA LIMITS:
XMIN=          6.000  XMAX=        366.000
YMIN=       2700.000  YMAX=       7320.000

EQUATION MATCHING CURVE IN FIGURE A1:
POWER:  Y=A*(X+X1)**B-Y1
A=   1758.4232       B=  0.22332923
X1=  0.              Y1=  0.

SUM SQR RESIDUALS=   2968343.15625  STD ERROR EST=       319.93227
NON-LINEAR CORR= 0.9578772
```

6 X 12-IN. CYLINDERS, PLASTIC MOLDS, TEST SERIES A

```
EXISTING DATA LIMITS:
XMIN=          6.000  XMAX=        366.000
YMIN=       2650.000  YMAX=       7320.000

EQUATION MATCHING CURVE IN FIGURE A2:
POWER:  Y=A*(X+X1)**B-Y1
A=   1782.0097       B=  0.22448219
X1=  0.              Y1=  0.

SUM SQR RESIDUALS=   1077657.17188  STD ERROR EST=       251.77688
NON-LINEAR CORR= 0.9832511
```

4 X 8-IN. CYLINDERS, PLASTIC MOLDS, TEST SERIES B

```
EXISTING DATA LIMITS:
XMIN=          3.000  XMAX=         56.000
YMIN=        440.000  YMAX=       4620.000

EQUATION MATCHING CURVE IN FIGURE A3:
COMMON LOG(LOG1):  Y=A1+A2*LOG(X+X1)+A3*(LOG(X+X1))**2
A1=  -1847.2255      A2=   5213.7581 .
A3=  -877.61094      X1=  0.

SUM SQR RESIDUALS=     483292.80078  STD ERROR EST=       122.89386
NON-LINEAR CORR= 0.9929694
```

Table J1 (Concluded)
EQUATIONS OF COMPRESSIVE STRENGTH VS. TIME

6 X 12-IN. CYLINDERS, PLASTIC MOLDS, TEST SERIES B

```
EXISTING DATA LIMITS:
XMIN=          8.000  XMAX=          28.000
YMIN=       2070.000  YMAX=        3780.000

EQUATION MATCHING CURVE IN FIGURE A4:
COMMON LOG(LOG1):  Y=A1+A2*LOG(X+X1)+A3*(LOG(X+X1))**2
A1=  -5175.0837      A2=   11609.142
A3=  -3827.8719      X1=  0.

SUM SQR RESIDUALS=    316543.26953  STD ERROR EST=      145.26832
NON-LINEAR CORR= 0.9650209
```

6 X 12-IN. CYLINDERS, STEEL MOLDS, TEST SERIES B

```
EXISTING DATA LIMITS
XMIN=          8.000  XMAX=         374.000
YMIN=       2800.000  YMAX=        7550.000

EQUATION MATCHING CURVE IN FIGURE A5:
COMMON LOG(LOG2):  Y=A1+A2*(X+X1)+A3*LOG(X+X1)
A1=  -503.02470      A2=  -4.4665068
A3=   3722.2272      X1=  0.

SUM SQR RESIDUALS=     90861.53320  STD ERROR EST=       77.82953
NON-LINEAR CORR= 0.9987327
```

Table J2
EQUATIONS OF STATIC MODULULS OF ELASTICITY VS. TIME

4 X 8-IN. CYLINDERS. PLASTIC MOLDS. TEST SERIES A

EXISTING DATA LIMITS

XMIN=	6.000	XMAX=	366.000
YMIN=	2.550	YMAX=	6.870

ALL CORRELATIONS FOR THESE DATA FELL BELOW ACCEPTABLE LEVELS
NO CURVE WAS RECOMMENDED

6 X 12-IN. CYLINDERS. PLASTIC MOLDS. TEST SERIES A

EXISTING DATA LIMITS:

XMIN=	6.000	XMAX=	366.000
YMIN=	1.800	YMAX=	6.870

EQUATION MATCHING CURVE IN FIGURE C2:
COMMON LOG(LOG2): Y=A1+A2*(X+X1)+A3*LOG(X+X1)

A1=	2.4691936	A2=	0.56026221E-02
A3=	0.27780496	X1=	0.

SUM SQR RESIDUALS= 1.94858 STD ERROR EST= 0.36042
NON-LINEAR CORR= 0.9212311

4 X 8-IN. CYLINDERS. PLASTIC MOLDS. TEST SERIES B

EXISTING DATA LIMITS:

XMIN=	3.000	XMAX=	28.000
YMIN=	0.620	YMAX=	3.750

EQUATION MATCHING CURVE IN FIGURE C3:
COMMON LOG(LOG1): Y=A1+A2*LOG(X+X1)+A3*(LOG(X+X1))**2

A1=	-2.2269048	A2=	6.8872105
A3=	-2.2304001	X1=	0.

SUM SQR RESIDUALS= 1.81092 STD ERROR EST= 0.24569
NON-LINEAR CORR= 0.9507452

Table J2 (concluded)
EQUATIONS OF STATIC MODULULS OF ELASTICITY VS. TIME

<u>6 X 12-IN. CYLINDERS, PLASTIC MOLDS, TEST SERIES B</u>

```
EXISTING DATA LIMITS:
XMIN=           8.000  XMAX=          28.000
YMIN=           1.750  YMAX=           3.750

EQUATION MATCHING CURVE IN FIGURE C4:
COMMON LOG(LOG1):  Y=A1+A2*LOG(X+X1)+A3*(LOG(X+X1))**2
A1=  -3.5431916      A2=   8.7405148
A3=  -2.9583689      X1=  0.

SUM SQR RESIDUALS=          0.61568  STD ERROR EST=         0.20260
NON-LINEAR CORR= 0.8760336
```

<u>6 X 12-IN. CYLINDERS, STEEL MOLDS, TEST SERIES B</u>

```
EXISTING DATA LIMITS (data modified by removing one point):
XMIN=           8.000  XMAX=          28.000
YMIN=           2.650  YMAX=           4.500

EQUATION MATCHING CURVE IN FIGURE C5:
COMMON LOG(LOG1):  Y=A1+A2*LOG(X+X1)+A3*(LOG(X+X1))**2
A1=   4.1814254      A2=  -4.0512569
A3=   2.8205340      X1=  0.

SUM SQR RESIDUALS=          0.58801  STD ERROR EST=         0.23120
NON-LINEAR CORR= 0.9205903
```

Table J3
EQUATIONS OF POISSON'S RATIO VS. TIME

4 X 8-IN. CYLINDERS, PLASTIC MOLDS, TEST SERIES A

EXISTING DATA LIMITS:

XMIN=	6.000	XMAX=	366.000
YMIN=	0.120	YMAX=	0.270

ALL CORRELATIONS FOR THESE DATA FELL BELOW ACCEPTABLE LEVELS
NO CURVE WAS RECOMMENDED

6 X 12-IN. CYLINDERS, PLASTIC MOLDS, TEST SERIES A

EXISTING DATA LIMITS:

XMIN=	6.000	XMAX=	251.000
YMIN=	0.120	YMAX=	0.330

ALL CORRELATIONS FOR THESE DATA FELL BELOW ACCEPTABLE LEVELS
NO CURVE WAS RECOMMENDED

4 X 8-IN. CYLINDERS, PLASTIC MOLDS, TEST SERIES B

EXISTING DATA LIMITS:

XMIN=	3.000	XMAX=	21.000
YMIN=	0.170	YMAX=	0.230

ALL CORRELATIONS FOR THESE DATA FELL BELOW ACCEPTABLE LEVELS
NO CURVE WAS RECOMMENDED

6 X 12-IN. CYLINDERS, PLASTIC MOLDS, TEST SERIES B

EXISTING DATA LIMITS:

XMIN=	8.000	XMAX=	28.000
YMIN=	0.160	YMAX=	0.290

ALL CORRELATIONS FOR THESE DATA FELL BELOW ACCEPTABLE LEVELS
NO CURVE WAS RECOMMENDED

6 X 12-IN. CYLINDERS, STEEL MOLDS, TEST SERIES B

EXISTING DATA LIMITS:

XMIN=	8.000	XMAX=	28.000
YMIN=	0.170	YMAX=	0.290

ALL CORRELATIONS FOR THESE DATA FELL BELOW ACCEPTABLE LEVELS
NO CURVE WAS RECOMMENDED

Table J4
EQUATIONS OF DYNAMIC MODULULS OF ELASTICITY VS. TIME

4 X 8-IN. CYLINDERS, PLASTIC MOLDS, TEST SERIES A

EXISTING DATA LIMITS:
XMIN= 5.000 XMAX= 175.000
YMIN= 4.150 YMAX= 5.400

EQUATION MATCHING CURVE IN FIGURE G1:
COMMON LOG(LOG2): Y=A1+A2*(X+X1)+A3*LOG(X+X1)
A1= 3.7127070 A2= 0.14804679E-02
A3= 0.61746206 X1= 0.

SUM SQR RESIDUALS= 0.00919 STD ERROR EST= 0.02658
NON-LINEAR CORR= 0.9960764

6 X 12-IN. CYLINDERS, PLASTIC MOLDS, TEST SERIES A

EXISTING DATA LIMITS
XMIN= 4.000 XMAX= 175.000
YMIN= 3.950 YMAX= 6.300

EQUATION MATCHING CURVE IN FIGURE G2:
COMMON LOG(LOG1). Y=A1+A2*LOG(X+X1)+A3*(LOG(X+X1))**2
A1= 2.7062669 A2= 2.2927733
A3= -0.33156281 X1= 0.

SUM SQR RESIDUALS= 0.03701 STD ERROR EST= 0.06412
NON-LINEAR CORR= 0.9950297

4 X 8-IN. CYLINDERS, PLASTIC MOLDS, TEST SERIES B

EXISTING DATA LIMITS:
XMIN= 3.000 XMAX= 17.000
YMIN= 1.850 YMAX= 4.200

EQUATION MATCHING CURVE IN FIGURE G3:
COMMON LOG(LOG2): Y=A1+A2*(X+X1)+A3*LOG(X+X1)
A1= -0.56753778 A2= -0.15407688
A3= 6.0113752 X1= 0.

SUM SQR RESIDUALS= 0.05676 STD ERROR EST= 0.06608
NON-LINEAR CORR= 0.9959400

Table J4 (concluded)

EQUATIONS OF DYNAMIC MODULULS OF ELASTICITY VS. TIME

6 X 12-IN. CYLINDERS, PLASTIC MOLDS, TEST SERIES B

```
EXISTING DATA LIMITS:
XMIN=            7.000  XMAX=           17.000
YMIN=            3.450  YMAX=            4.200

EQUATION MATCHING CURVE IN FIGURE G4:
COMMON LOG(LOG2):  Y=A1+A2*(X+X1)+A3*LOG(X+X1)
A1=  0.45509709      A2= -0.99221442E-01
A3=    4.3611571     X1=  0.

SUM SQR RESIDUALS=          0.00453  STD ERROR EST=          0.02379
NON-LINEAR CORR= 0.9945321
```

6 X 12-IN. CYLINDERS, STEEL MOLDS, TEST SERIES B

```
EXISTING DATA LIMITS:
XMIN=            7.000  XMAX=           21.000
YMIN=            4.200  YMAX=            5.250

EQUATION MATCHING CURVE IN FIGURE G5:
COMMON LOG(LOG2):  Y=A1+A2*(X+X1)+A3*LOG(X+X1)
A1=    3.1240532     A2=  0.34996986E-01
A3=  0.98836399      X1=  0.

SUM SQR RESIDUALS=          0.01748  STD ERROR EST=          0.06611
NON-LINEAR CORR= 0.9857134
```

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